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Investigations of Marine Environmental Quality in Halifax Harbour

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Les numéros 1 à 456 de cette série ont été publiés à titre de rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de rapports techniques de la Direction générale de la recherche et du développement/Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

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ABSTRACT

Nicholls, H.B. (Ed.). 1989. Investigations of Marine Environmental Quality in Halifax Harbour. Can. Tech. Rep. Fish. Aquat. Sci. 1693: v + 83 p.

This report brings together several papers pertaining to the marine environmental quality of Halifax Harbour, Nova Scotia. The papers describe research conducted by the federal departments of Fisheries and Oceans, Energy, Mines and Resources, and the Environment. The results of sedimentological studies, benthic biological studies, and investigations of trace metal concentrations in water and suspended particulate matter are presented. A review of the physical oceanography (including modelling) of the Harbour is included. The results of limited investigations of contaminants in lobsters and their bacteriological quality are presented as appendices, as is a bibliography of scientific publications pertaining to the Harbour. Environmental quality issues relevant to sewage treatment, specifically with reference to proposals for a Halifax-Dartmouth metropolitan area sewage treatment facility with an outfall into the harbour, are identified and discussed.

RÉSUMÉ

Nicholls, H.B. (Ed.). 1989. Investigations of Marine Environmental Quality in Halifax Harbour. Can. Tech. Rep. Fish. Aquat. Sci. 1693: v + 83 p.

Le présent rapport regroupe plusieurs documents relatifs à la qualité de l'environnement marin du port d'Halifax (Nouvelle-Écosse), qui décrivent les recherches effectuées par le ministère fédéral des Pêches et des Océans, celui de l'Énergie, des Mines et des Ressources et celui de l'Environnement. Il expose les résultats d'études sédimentologiques, d'études biologiques sur le milieu benthique, de recherches sur les particules en suspension ainsi que sur les concentrations de métaux traces présentes dans l'eau. On y trouve également un aperçu de l'océanographie physique (faisant appel à la modélisation) du port d'Halifax et, en annexes, les résultats de recherches limitées sur les contaminants présents dans le homard et sur leur qualité bactériologique, ainsi qu'une bibliographie des publications scientifique se rapportant au port. Enfin, on y aborde divers problèmes de qualité de l'environnement ayant trait à l'épuration des eaux usées, à la lumière des projets d'installation d'une usine d'épuration des eaux de la région métropolitaine de Halifax-Dartmouth qui comporterait un émissaire d'évacuation dans le port.

ACKNOWLEDGMENTS

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INTRODUCTION

Numerous scientific studies by government, universities and industry have been undertaken in the waters that comprise Halifax Harbour. A recent bibliography of Halifax Harbour for example, which is included as Appendix 'C' to this report, contains over 200 citations. The continuing use of the Harbour for a variety of purposes, and in particular for the disposal of sewage, has led to the need for increased communication and cooperation among the various laboratories involved in these research activities. For example, in 1988 the federal Departments of Environment (DOE), Fisheries and Oceans (DFO), and Energy, Mines and Resources (DEMR) undertook a collaborative project pertaining to the marine environmental quality of the Harbour that also involved a local oceanographic company (OceanChem Group).

On account of its location within Halifax Harbour, the Bedford Institute of Oceanography (BIO) has undertaken numerous studies within this body of water. It should be emphasized that many of the studies were undertaken because the Harbour represents a convenient and easily accessible body of water to BIO, and not because of its special nature or interest. Nevertheless, Halifax Harbour has been extensively studied compared with the majority of other similar bodies of water in eastern Canada.

For the purpose of this report, Halifax Harbour is generally considered to be that body of water landward of a line drawn between Chebucto Head and Devils Island. This corresponds to the definition given in the Sailing Directions for Nova Scotia, which state in part that "the Harbour is entered between Devils Island and Chebucto Head". Thus the Harbour includes Bedford Basin, The Narrows, the Northwest Arm and Eastern Passage. The area seaward of the above line and known as the "Approaches to Halifax Harbour" (refer to Canadian Hydrographic Services Chart #4237), is also of interest with respect to the sewage disposal issue covered by this report.

Currently, i.e. July 1989, sewage from Halifax and Dartmouth is discharged into Halifax Harbour in an untreated state via 40 outfalls. A central treatment plant is proposed, involving primary treatment, which will discharge into the Harbour through a single outfall. The selection of a location for the plant, including the outfall, has resulted in considerable controversy.

There is a small commercial lobster fishery throughout Halifax Harbour and in the Approaches, and also small groundfish and finfish fisheries in the outer harbour and in the Approaches. Recreational fishing, for such species as pollock, is popular. Extensive lobster holding facilities are located in the area.

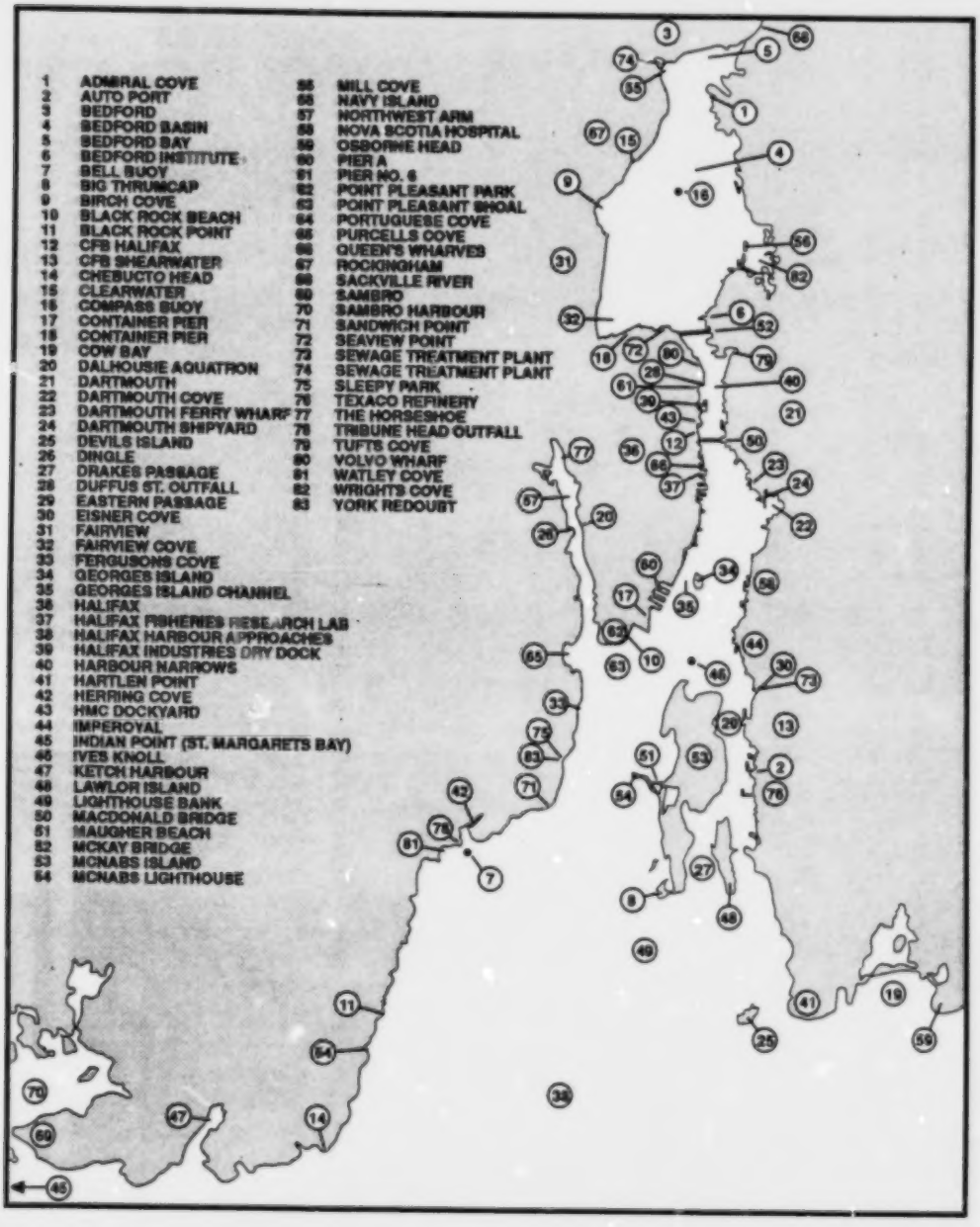
The Department of Fisheries and Oceans Science Sector at BIO and at the Halifax Fisheries Research Laboratory has ongoing research projects pertaining to Halifax Harbour and relevant to the sewage disposal issue. In this regard it works closely with local units of the Department of Energy, Mines and Resources (i.e. the Atlantic Geoscience Centre located at BIO) and the Department of the Environment. In October 1988, these three departments established a science advisory committee--the DFO/DEMR/DOE Science Advisory Committee on Halifax Harbour Sewage Disposal--to provide a focal point for scientific coordination and response on this matter. In addition to scientific staff, representatives of DFO's regional Habitat Management and Inspection Branches also sit on this committee.

In view of a widespread local interest in the Halifax Harbour sewage disposal issue and the need to make information readily available on federal research pertaining to this subject, including interpretations of data published elsewhere, the DFO/DEMR/DOE Science Advisory Committee decided to produce a report providing such information. This document is the result. It comprises accounts of investigations underway, or recently completed, as of March 1989, as well as descriptions of certain other activities. It does not include subsequent investigations, e.g., the May 1989 Halifax Harbour geological-geophysical survey, undertaken by the Atlantic Geoscience Centre of DEMR. It should be emphasized that the papers comprising this report describe separate research investigations and thus do not represent a cohesive study. It had not previously been the intention to publish them together in a single volume.

The report opens with a short discussion by the DFO/DEMR/DOE Science Advisory Committee on Halifax Harbour Sewage Disposal that places the research described into context with respect to the sewage disposal issue, and identifies outstanding issues and future research requirements. The first paper in the report outlines investigations of sea-floor surficial sediments which have been underway since 1986 and remain ongoing. Work began in 1986 as a DFO project and was expanded in 1988 through collaboration with DOE, DEMR and a local oceanographic company (OceanChem Group). A large number of samples (224) have been collected from the Harbour and analyses have been undertaken (and are continuing) for a variety of parameters, including several heavy metals. This research is relevant to a number of concerns pertaining to the sewage disposal issue including that of the possibility of contaminated sediments in the Harbour being oxidized once the sewage input to the Harbour is eliminated or decreased, resulting in the release of contaminants to the water column. The second paper describes the results of an underwater photographic survey, together with limited sediment sampling, that was undertaken in the vicinity of Herring Cove in late 1987 to assess the environmental impact of discharges from the existing sewage outfall at Tribune Head. This investigation was in response to questions raised concerning possible marine benthic habitat deterioration due to discharge from the outfall. Dissolved and particulate trace metal distributions in Halifax Harbour are the subject of a third paper, which gives the results of analyses on water samples that were collected at seven locations in January 1989. The fourth paper is different from the others in that it does not describe a specific research investigation but provides an overview of BIO's involvement pertaining to the physical oceanography and modelling of Halifax Harbour since the 1970's. In addition to the four papers, the report contains three appendices. The first reports on investigations of heavy metal, polycyclic aromatic hydrocarbon, and polychlorinated biphenyl concentrations in a small number of samples of American lobsters collected from Halifax Harbour in May 1988 and January 1989. The second provides the results of the microbiological examination of lobsters captured on various dates in 1988, the object of which was to determine the microbiological quality of the lobsters with respect to their use as food. The third appendix is a bibliography of scientific reports and publications pertaining to Halifax Harbour

In addition to the individual authors, members of the DFO/DEMR/DOE Science Advisory Committee on Halifax Harbour Sewage Disposal contributed to preparing this report. Membership of this committee comprises Wayne Barchard (DOE), Dale Buckley (DEMR), Andre Ducharme (DFO Habitat Management), Barry Hargrave (DFO Science), Don Lawrence (DFO Science), Brian Nicholls (DFO Science) and Gaye Sims (DFO Inspection).

In order to expedite publication, the papers contained in this report have been subjected to internal review. Each individual paper predominantly represents the views of its author(s).



Map of Halifax Harbour

DISCUSSION

HALIFAX HARBOUR MARINE ENVIRONMENTAL QUALITY

by

DFO/DEMR/DOE Science Advisory Committee
on Halifax Harbour Sewage Disposal [1]

[1] With contributions from J.M. Bewers (Science Sector, Scotia-Fundy Region, Department of Fisheries and Oceans) and D. MacNeil (Inspection Services Branch, Scotia-Fundy Region, Department of Fisheries and Oceans).

Marine environmental quality (MEQ) can be defined as the condition of the marine environment measured relative to each intended use of that environment (Wells *et al.*, 1986; Côté, 1989). It is usually assessed quantitatively in different environmental compartments, on temporal and spatial scales, and is measured relative to objectives and limits set by environment, health, and resource agencies. Within the context of the above definition and with respect to Halifax Harbour, it follows that three pertinent questions are:

- What are the intended future uses of Halifax Harbour?;
- What is the environmental quality of Halifax Harbour?; and
- What changes can be expected in environmental quality due to alterations to sewage collection/treatment/disposal systems?

While the majority of the papers in this monograph do not quantitatively assess MEQ according to the above definition, all have a bearing on it. It follows that any evaluation of environmental conditions in Halifax Harbour must be made against the perspective of the desired uses (i.e., recreational, industrial, fisheries, etc.) of the system. The primary task then will be to establish a set of mutually compatible uses of the harbour in a sociopolitical framework. Once this has been done, it will be possible to define the kinds of environmental conditions and features that permit these uses. At this latter stage of the exercise, the limited assessment of conditions contained in this document will form a starting point for determining likely variations from required conditions both now and after any changes have been made to the sewage collection, treatment and disposal system.

It is clear that Halifax Harbour is not pristine. Its use as a receiving environment for sewage and associated domestic and industrial wastes for more than a century has inevitably resulted in undesireable contamination of the system. This is evidenced, for example, by shellfish closures in adjacent waters due to fecal coliform contamination, risks associated with swimming in waters contaminated with human fecal material, and aesthetic objections to the visible signs of sewage discharge. The studies described herein provide limited insight as to the extent of this 'pollution' (by international definition implying deleterious effects). In particular, they provide limited information on conditions and processes in Halifax Harbour with emphasis on water circulation, sedimentological, benthic biological, and chemical conditions. Each of these papers emphasize the heterogeneity of conditions in the harbour that complicates drawing unambiguous and clear-cut conclusions about the impact resulting from current practices and the potential for future disturbances that could result from further development, including alterations to sewage collection, treatment, and disposal from the Halifax-Dartmouth-Bedford conurbation. At the outset, however, it should be noted that the planned new sewage treatment system will contribute to a cleaner harbour.

Outlined below are some of the major issues described in, or arising from, the papers comprising this document.

(i) Release of metals into harbour waters from contaminated sediments

Enhanced concentrations of metals in the harbour sediments pose an environmental concern because of the potential for these metals to be released or remobilized from the sediments as a result of the reduction of organic matter input when primary/secondary sewage treatment facilities come on-line. These remobilized metals could become available to the organisms in the harbour, and ultimately the human population through the food chain. The mechanisms through which such remobilization could take place are complex and difficult to quantify. Each metal has a different geochemical reactivity and response to changing environmental conditions. The biological uptake of each metal is unique both in terms of the organism and the chemical reactivity of the metal.

Chapter 1 points out that the contaminated sediments are in a state of strong chemical reduction. This condition exists, in part, because of the large quantity of organic matter that is being deposited in the harbour. Bacteria oxidize some of this organic debris, causing consumption of dissolved oxygen at or near the sediment-water interface. Immediately below this boundary, biogeochemical reactions result in the chemical reduction of sulfates to sulfides, which precipitate metals as sulfides. As long as there is continued deposition of organically-rich material, and the sediments are not physically disturbed by dredging or other activities, most of the chemical contaminants will remain in a quasi-stable bound state in the sediments.

Natural processes of diagenesis can result in the release of some metals from sediments into associated pore water. If depositional conditions change, with a decrease in the amount of organic matter being deposited, there will be less oxygen demand at the sediment-water interface and deeper oxygen penetration into the sediments. Under these new conditions, some of the previously precipitated metal sulfides could be oxidized and some of the presently preserved organic compounds decomposed. These new conditions would increase the solubility of some of the metals, with the possibility of forming new metal-organic compounds and complexes. Increased concentrations of dissolved metals in the pore water and enhanced in-faunal activity would increase the transport of metals out of the sediments into the overlying water column. Some of these metals could become available to organisms living in/on the sediments or in the water above the sediments. This scenario of changing environmental conditions is possible if the input of sewage sludge into Halifax Harbour were to be drastically decreased. However, it should be noted that the supply of organic matter from phytoplankton production, river inflow, and freshwater runoff will continue.

The important question with regard to this process and its implications for the development of a sewage treatment facility is how significant is the magnitude of this remobilization process likely to be. To answer this, several variables must be determined: (1) what will be the rate of diffusion of oxygen and other oxidants into sediments with various quantities and types of organic matter and various geotechnical properties?; (2) how will regional depositional rates be changed, and what effect will this have on the penetration of oxygen into the sediments?; (3) what type of complexes will be formed by the oxidized metals and organic matter?; (4) what will be the diffusion rate of contaminants out of the sediments?; (5) what will be the bioavailability of the remobilized contaminants?; (6) how efficient will the oceanographic circulation be in advecting the remobilized contaminants out of the harbour system?; and (7) what is the mass contaminant balance between inputs from the sewers and the total remobilization of these materials from the harbour sediments? In addition to these considerations, it will also be important to determine how the establishment of new benthic biological communities will affect the rate of bioturbation, and thus the release of contaminants from the older contaminated sediments. Additional work will be required to predict the result of the above processes.

(ii) Impacts of sewage outfall discharge on benthic habitat

Chapter 2 reports in part on bottom photography, together with limited sea-floor surface sediment sampling, along four nearshore transects near Tribune Head on the western shore of Halifax Harbour. The area is one that is influenced by an exiting raw-sewage outfall and the survey was intended to provide information

on the condition of the benthic habitat. It did not attempt to assess aesthetic or other concerns. While the results did not point to serious deterioration of the habitat, i.e., dense beds of macrophytes were observed to cover part of the steeply sloped rocky bottom and no debris or discolouration of surface sediments were noted, care would need to be taken in extrapolating these results of a limited survey of a single raw-sewage outfall to a common, treated outfall, situation.

(iii) Toxicity of trace metals to planktonic and benthic organisms

Based on the studies reported in Chapter 3, levels of dissolved trace metals in seawater in Halifax Harbour are roughly comparable with those in other inshore waters of the Canadian east coast. These levels would not be expected to be toxic to planktonic organisms, especially since part of the total dissolved concentration can be expected to be complexed with dissolved organic matter, which decreases their toxicity. Similarly, in sediments, the complexation and binding of trace metals to organic matter reduces the toxicity to benthic organisms. The toxicity of trace metals associated with sediments to benthic fauna is also determined by concentration gradients within and above the sediments. Micro-organisms and benthic fauna of various sizes can experience concentration gradients over horizontal and vertical distances equivalent to their cell or body size. For example, the tube dwelling polychaete *Spiochaetopterus*, which is abundant in some areas of Bedford Basin, builds a stiff-walled mucous polysaccharide tube that may penetrate into the sediment up to 30 cm but projects a few centimeters above the sediment surface. Worms can live deep in "chemically"-reducing sediment and pump oxygenated water from above the sediment surface through their burrows. Concentrations of dissolved and particulate compounds that these animals experience are not those of the surrounding deposits, but of water a few centimeters above the sediment surface. Further studies are needed to measure concentrations of various trace metals in tissues of benthic biota from various regions of Halifax Harbour and to determine if present levels are stressful.

(iv) Eutrophication

Concern has been expressed that treated sewage effluent aggregated and discharged via a single outfall into Halifax Harbour will result in nutrients (nitrates and phosphates) being concentrated in a specific area as opposed to being spread out as is the case with the existing separate raw sewage outfalls. Excess nutrients can stimulate phytoplankton and algal production, followed by depletion of dissolved oxygen due to bacterial decay, which in turn may have deleterious effects on fish and lead to reduced water quality. In particular, there can be problems in inlets where flushing and currents are generally restricted. While this issue is not covered specifically in the papers of the monograph, several have a bearing on it. A recently published report (Roy, 1989) describes the formation of the spring phytoplankton bloom in Bedford Basin. Sewage discharge represents a source of freshwater to the inlet that will be enriched with dissolved inorganic nitrogen and other nutrients. If the volume is sufficient to cause local stratification in the area of effluent release when solar radiation is high, then abnormal phytoplankton blooms may occur. The conditions of stratification would have to be sustained for periods of several days or longer for phytoplankton biomass accumulation to reach bloom conditions. Additional research may be required to resolve this issue. The topic is one of increasing concern internationally and has recently been ranked by the United Nations Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP) as the primary concern in relation to the long-term health of the ocean ecosystem. Eutrophication may also play a role in the incidence of toxic phytoplankton blooms.

(v) Contaminants in lobster

The high levels of heavy metals found in the sediments of Halifax Harbour and reported in Chapter 1 led to questions about water quality, which in turn raised concerns about marine biota, specifically lobster. A survey of water quality was undertaken (Chapter 3). In addition, lobsters from several locations were analyzed for heavy metals, polycyclic aromatic hydrocarbons (PAHs)

and polychlorinated biphenyls (PCBs) (refer to Appendix 'A'). Because the investigations were undertaken during the winter months when water temperatures were low, an insufficient number of lobsters was captured. The results were inconclusive and the study is to be repeated in the early fall of 1989, immediately prior to the commercial lobster fishing season, at which time it is expected that sufficient samples will be obtained. If this further work indicates that there is a problem, an expanded program of research would be required to determine its extent, the impact on commercial fisheries, and the effects of sewage treatment.

The results of the limited microbiological investigations referred to in Appendix B did not reveal any indication that the bacteriological quality of the lobsters would pose a hazard to human health, providing that the lobsters are properly handled and cooked. However, in conjunction with the fall 1989 studies referred to above, organoleptic tests and additional microbiological work are to be undertaken.

(vi) Physical oceanographic concerns

The main limitation of recent physical oceanographic modeling of Halifax Harbour described in Chapter 4 is the assumption of vertically uniform conditions; earlier data show year-round layered flow in The Narrows and stratified conditions in the entire harbour during most of the year. Freshwater inflow, principally via the Sackville River, offers a plausible mechanism for this, although not directly proven. The oceanographic survey now underway and referred to in Chapter 4 will measure nearsurface and nearbottom flows at six sites in the harbour continuously for a two-month period.

Conventional sewage discharge practice uses a bottom diffuser so that the buoyant plume entrains up to fifty times it initial volume of surrounding water on its rise to the surface, and is thereby greatly diluted. Conventional placement of discharges is such that buoyant plumes are carried seaward. However if there is a deep counter flow then any particulate matter settling out from the plume, or materials released from existing bottom sediments, might be carried landward.

Any rearrangement of freshwater due to sewage works (i.e., changing from multiple inner harbour inputs to a single outer harbour one) would not on an annual basis significantly upset the existing flow patterns as the sewage volume is only 15% of the total annual freshwater inflow. However, natural runoff is at a minimum in the summer months, at which time the sewage plant discharge could reach 50-75% of the total and therefore could be important.

* * * * * * * * * *

This technical report describes several federal studies relevant to the marine environmental quality (MEQ) of Halifax Harbour and raises a number of related issues. It will be evident to the reader that our current state of knowledge of the MEQ of the harbour is limited and that additional studies, several of which are referred to in this document, would be required to enhance our limited understanding. In their 1989 report, the Halifax Harbour Cleanup Review Committee (Halifax Harbour Cleanup Review Committee, 1989) list as one of their recommendations the need for a comprehensive monitoring program of the harbour to include both before-plant and after-plant measurements of the appropriate variables. The DFO/DEMR/DOE Science Advisory Committee would endorse the need for such a program. In conclusion, it should be noted that the installation of a sewage treatment plant and associated facilities will not completely end the contamination of Halifax Harbour. Much will be achieved, but other sources, including remobilization from existing sediments, stormwater runoff, river discharge and atmospheric fallout, will continue to introduce contaminants into the harbour. Likewise, the direct discharge of toxic materials by industries and households into the sewage system will continue to be of concern since these materials are not completely removed by conventional sewage treatment.

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CHAPTER 1

GEOCHEMICAL CHARACTERISTICS OF SURFACE SEDIMENTS

by
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ABSTRACT

Surface sediment samples collected in 1986 and 1988 from 224 stations within Halifax inlet (Bedford Basin, Halifax Harbour, the Northwest Arm and Harbour Approaches) were analyzed for grain size, total and organic carbon and total elemental analysis for silicon (Si), aluminum (Al), calcium (Ca), magnesium (Mg), potassium (K), titanium (Ti), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), nickel (Ni), lead (Pb), mercury (Hg), and lithium (Li). Measurements of porosity, oxidation reduction potentials (Eh), oxygen uptake and dissolved carbon dioxide (CO_2) in pore water were carried out with samples collected in 1988.

Relative to other estuarine and coastal bays in eastern Canada, sediments in Halifax inlet are enriched with organic carbon and the metals (Cu, Zn, Pb, and Hg) characteristic of sewage and industrial contamination. Significant correlations ($p>0.99$) occurred between these metal concentrations and organic carbon content but no significant relationships existed with the percentage of mud in samples.

Anomalous concentrations of metal and organic carbon were identified relative to mean values in other coastal areas, or for all of Halifax inlet. Sources from municipal or domestic sewage (greatest enrichment of Cu and Hg) could be separated from those of solid and industrial wastes (dominated by Pb and Zn) using this approach.

Except for stations in the approaches to Halifax Harbour, most surface sediments were reduced with Eh values $< +100$ mv. Oxygen uptake was ten-fold greater in these samples than those from sites within the Harbour approaches indicative of chemical demand due to sulfide oxidation. Most metals are probably bound as insoluble sulfides with the highest concentrations accumulated in sediments enriched with organic carbon. Dissolved CO_2 in pore water also tended to be greatest at stations with low Eh values as expected if CO_2 arises from bacterial sulfate reduction.

Patterns of contaminant concentrations within the inlet showed 12 areas associated with major sewage outfalls and industrial sources. Contours of concentrations imply that rapid adsorption or precipitation of metals on sediments limits dispersion away from source areas. These patterns also imply that contaminated sediments are dispersed inward along the Harbour water front, and that the inlet is not efficient in dispersing contaminants out to the open marine area.

(GSC Contribution No. 26289)

INTRODUCTION

Between 1986 and 1988 two series of bottom sediment samples were collected from Halifax inlet (Fig. 1-1). One of these series of samples ("B") consisting of 102 Van Veen grabs was analyzed for organic carbon, nitrogen content, redox potential, and oxygen uptake. Results were reported by Prouse and Hargrave (1987). A second series of 122 samples ("C") collected in 1988 provided a total of 224 samples that were used in a chemical and sedimentological study of the quality of surficial sediments throughout Halifax inlet. Station locations and data from these analyses of the top cm of the sediment have been reported in a two volume data report by Buckley *et al.* (1989). The data in this report include sediment size classification, total and organic carbon, and total elemental analyses for the elements Si, Al, Ca, Mg, K, Ti, Fe, Mn, Cu, Zn, Ni, Pb, Hg, and Li for samples from both the "B" and "C" series. Results in the data report from measurement of porosity (water content), CO_2 and redox potential are provided for only the "C" series samples. The Buckley *et al.* (1989) report provides detailed information on the precision and accuracy of the analytical techniques used to obtain the data, and includes 31 maps (1:25,000 scale) that provide information on the distribution of sedimentological and chemical characteristics in the inlet. However, no interpretation of the data in terms of the significance of any contamination levels or sources of geochemical variations was provided. The purpose of the present report is to provide some of these interpretations. It is not intended that all chemical data will be discussed in detail, however, some explanation of the significance or use of the major element data will be provided. Emphasis will be placed on interpretation of results obtained from analysis of the most environmentally sensitive elements, such as organic carbon, Cu, Zn, Pb, and Hg, as well as measurements of CO_2 and redox potential in the sediments.

SEDIMENT OXIDATION - REDUCTION POTENTIALS

Oxidation-reduction reactions within sediments generate free electrons that may be measured as a redox (Eh) potential between a platinum wire and a reference electrode (usually a calomel KCL electrode). The Eh potential corrected for the reference potential in millivolts is a measure of free electron activity arising from many coupled reactions. While potentials do not give information about individual reactions, values can be used to indicate whether oxidizing or reducing conditions are present.

Microbial oxidation of organic carbon through different bacterial metabolic processes can create steep gradients in Eh near the sediment surface. However, different metabolic processes are carried out by micro-organisms within characteristic ranges of potentials (Table 1-1). Thus Eh may be used to describe in a general way the electron acceptors used in bacterial metabolism. This may be linked to both the organic carbon content and the concentration of trace metals in sediments and it is a useful way in which to identify the presence of oxidizing or reducing conditions.

Table 1-1. Microbial processes, products and characteristic redox potentials for organic carbon oxidation

Process	Electron Acceptor	Reaction Products	Eh (mv) Range
Aerobic Respiration	O_2	CO_2, H_2O, biomass	+500 - +800
Nitrate Reduction	NO_3	NO_2	+300 - +500
Metal Reduction	MnO_2 $FeSO_4$	Mn^{++} Fe^{++}	+100 - +400
Sulfate Reduction	SO_4	SH^-, acetate	-100 - -400
Carbonate Reduction	CO_2	CH_4	-800
Fermentation	organic carbon	H_2, CO_2, organic acids	a variety of Eh values

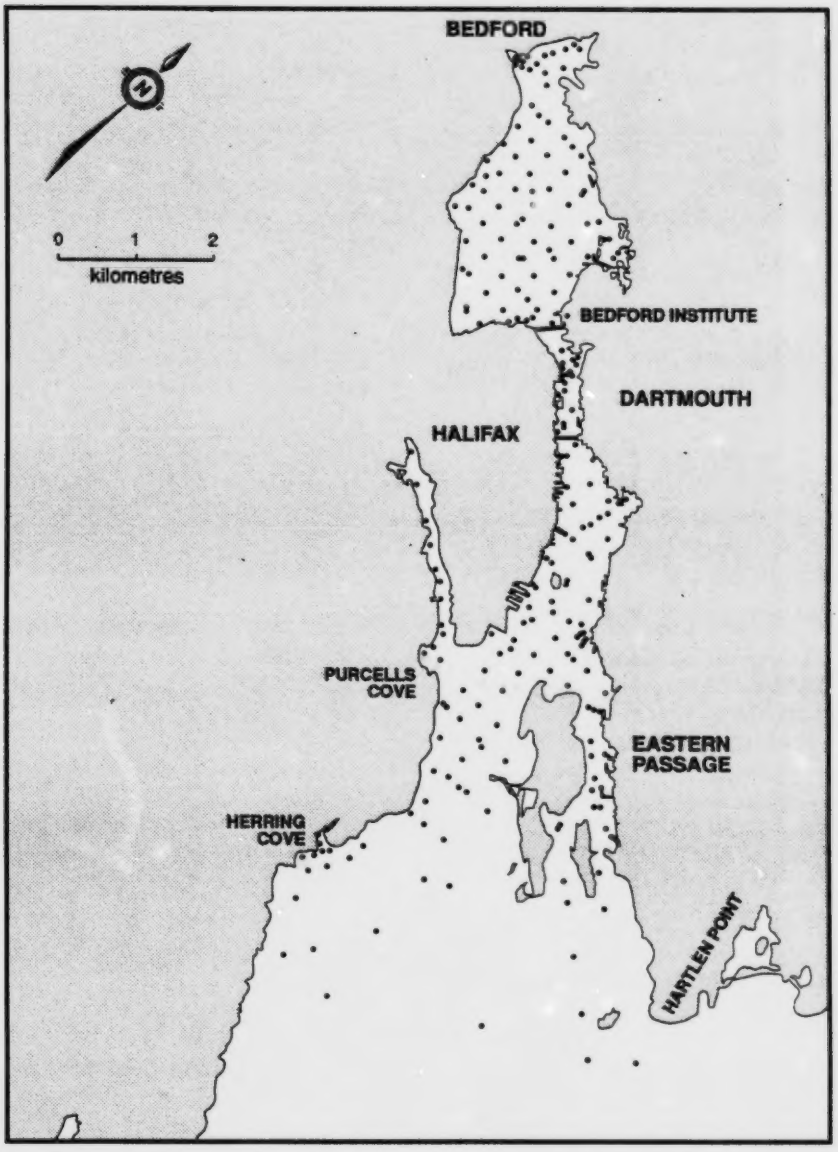


Figure 1-1 Location of stations from which surface sediment samples were collected in 1986 and 1988.

While there is overlap in potentials for various metabolic reactions and these processes may occur simultaneously, the ranges of values can be used to compare the reducing activity in sediments and to relate this to particular metabolic reactions at least in a qualitative sense. Oxygen does not control Eh directly but strongly reducing conditions with abundant free electrons and low potentials do not occur in the presence of oxygen. However, organic acids may be reducing and these can coexist with oxygen at Eh values $> +300$ mv. There may also be microsites of reduced sediment within aerobic sediment particularly if organic matter is present in large particles which within themselves create reducing conditions. Simultaneous measurements of dissolved oxygen, sulfide ions and sulfate are required to confirm that sediments are actually reducing and anoxic.

Steep gradients in Eh often occur at the sediment water interface in muddy sediments due to the limited penetration of dissolved oxygen. Thus, the surface 0.5 cm of sediment was removed from grabs by a stainless steel spatula and homogenized in a glass vial before measurement of Eh potentials in the present study to provide measurements of potentials representative of the sediment surface.

Poisoning of platinum electrodes by sulfides may also change measured potentials between successive determinations especially in reducing sediments. We avoided this by cleaning the platinum electrode tip with a fine abrasive powder after each measurement and standardizing each determination by an initial reading in aerated seawater. The deviation from an average value ($n=10$) for aerated seawater at the start of each sampling day was added to measured potentials. Electrodes were standardized in a quinhydrone solution ($+275$ mv., pH 7.0, 20° C) and with cleaning and standardization to aerated seawater, replicate measurements for a homogeneous sediment sample gave a standard deviation of $\pm$ 30 mv. Stabilization of Eh readings requires variable time periods depending on the coupled oxidation-reduction reactions present in a sample. Sandy sediments with Eh values $> +200$ mv and no apparent reducing layer stabilize within 30 sec. Reduced sediments (Eh $< +100$ mv) require 1 to 2 min to achieve a stable value. Methods for measurement of Eh potentials are fully described in Buckley *et al.* (1989).

DISSOLVED CARBON DIOXIDE IN SEDIMENT PORE WATER

All microbial reactions listed in Table 1-1 that oxidize organic carbon in sediments, whether they involve oxygen (aerobic metabolism) or an alternative electron acceptor (anaerobic metabolism) generate CO_2. Non-biological processes such as dissolution of inorganic carbonates may also enrich pore water with CO_2. Shell fragments from dead molluscs or planktonic and benthic protozoa that secrete calcareous shells (foraminifera) will slowly dissolve at rates dependent on the concentration gradient of carbonate in the surrounding water.

In poorly flushed sediments, such as silt-clay deposits, rates of pore water movement are slow and dissolution may be limited because saturation concentrations of dissolved carbonate are exceeded. The levels of dissolved CO_2 in sediment pore water may be useful to indicate where decomposition of organic matter has led to accumulation.

Vacutainer tubes filled with surface sediment samples used for redox measurements were sealed with rubber stoppers and inoculated with 1% buffered formalin solution to fix pore water for dissolved CO_2 measurements as described in Buckley *et al.* (1989).

SEDIMENT OXYGEN UPTAKE

An additional measurement of oxidative activity in sediments was provided by determination of rates of oxygen uptake. Sulfate reduction usually dominates organic matter decomposition in marine sediments where anoxic conditions arise when oxygen is consumed. Solid phase sulfides that polymerize into pyrite (polysulfides) are produced and hydrogen sulfide accumulates during sulfate reduction. These compounds are oxidized by oxygen resulting in a chemically based oxygen demand in reducing sediments that is insensitive to poisoning with formalin. In addition, heterotrophic organisms (bacteria, and benthic animals of varying size classes - micro, meio and macrofauna) consume oxygen through respiration.

Total oxygen demand was measured by incubation of stirred slurries of sediment during short-term laboratory incubations with rates expressed on a sediment dry weight basis by methods described in Prouse and Hargrave (1987). The measurement can be considered as the maximum potential for oxygen consumption in disturbed sediment since reduced dissolved and particulate matter normally buried is exposed to aerated seawater. Respiration by organisms may also be stimulated by disturbance. However, the measurement provides relative rates of oxygen uptake for comparison with estimates of consumption in the water column.

SEDIMENTOLOGICAL AND GEOCHEMICAL MEASUREMENTS

Sedimentological analyses consisted of measurement of the quantity of gravel, sand, silt and clay content in the sediment samples. The precision and accuracy of these measurements is provided in Buckley *et al.* (1989).

The elemental analyses were carried out by a method known as a total decomposition technique (Buckley and Cranston, 1971) which is intended to measure the total amount of the element present in the sample, regardless of the mineral or chemical complex form in which the element may be present. Thus, the results from these analyses can not be directly interpreted to show the potential of the element to be reactive or labile. Special analytical methods are required to determine the proportion of the total element concentration that might be reactive under certain conditions of changed pH, redox conditions, or decomposition of the organic matter. Some of these special analytical techniques are now being applied to these samples, and such data will be available at a later date.

All of the elemental analyses were carried out on the total unfractionated sediment samples. This means that no separation of specific sediment sizes was performed prior to the chemical analyses. The implication of this choice in the analytical approach will be discussed in some detail later in this report. It is well known that some metals are preferentially included or adsorbed in the finest sediment particles, therefore samples with high percentages of sand may mask highly concentrated amounts of metal contained in the small proportion of silt or clay that is present in the sediment. Similarly, organic matter, because of its low density, tends to accumulate together with fine grained mineral components of the sediment. Therefore coarse grained sands and gravels may have low organic carbon content, but the fine fraction of this sediment may contain nearly all of the organic carbon found in the total unfractionated sample.

GEOCHEMICAL SIGNIFICANCE OF ELEMENTAL COMPOSITION OF SEDIMENTS

The significance of the concentrations and variability of the 15 elements included in the analyses of the sediment samples from Halifax inlet can be understood by knowledge of the common geochemical associations and characteristics of the individual elements. Elements commonly found in marine sediments are classified as major, minor or trace elements. Major elements are those elements that make up the primary composition of silicate or common sedimentary minerals. These include Si, Al, Ca, Mg, K, and Fe. Minor elements are those that are commonly present in the lattice of some minerals but in concentrations less than one percent of the total composition. Included in this classification will be Ti, Mn, and Li. Trace elements are normally present in concentrations less than 1000 ppm and are commonly present as oxides, oxyhydroxides, sulfides or organic complexes, as secondary additives to the detrital mineral matrix. These elements include Cu, Zn, Ni, Pb, and Hg. Carbon is present in marine sediments as a major or minor element depending on the amounts of calcium carbonate ($CaCO_3$), and/or organic matter. For this reason carbon is determined by two techniques; one which determines the amount of total carbon, and one which determines the amount of carbon present in organic matter. The difference between these two analytical determinations is calculated as the quantity of inorganic carbon (usually in the form of carbonate). For general references to the geochemistry of these elements the reader may consult the Handbook of Geochemistry edited by Wedepohl (1972 and subsequent years) or one of the more specialized texts on marine geochemistry, such as Riley and Skirrow (1965).

Silicon (Si) is one of the most abundant elements on Earth. It is the major constituent in most rock-forming minerals. In sediments it is

present in the common detrital minerals, quartz, feldspars, clay minerals (phyllosilicates), and a wide variety of other heavy and light minerals. Variations in concentrations of Si is most often associated with variations in the amount of detrital quartz. In some deep sea sediments Si may be present in the amorphous mineral opal, as a result of accumulation of large quantities of diatom skeletons. In Halifax inlet variations of Si in the sediment is most likely to be directly related to the texture, with more Si present in the sediments having the higher sand content. In some samples Si may be inversely related to the organic carbon content, where high concentrations of organic matter dilute the content of inorganic mineral constituents.

Aluminum (Al) is also an abundant rock-forming element and is most often associated with the broad classification of minerals called aluminosilicates. These include the common sedimentary minerals phyllosilicates, feldspars and amphiboles. Variations in the concentration of Al in sediments may be associated with changes in the clay mineral content (therefore the fine-grained size fraction of the sediment), or with the content of feldspars in the sediment (usually more abundant in the coarse-grained size fractions of the sediment). It is thus difficult to directly attribute Al variations to a single sedimentary characteristic. However, ratios of other elements to Al are commonly used to normalize the detrital mineral content to any authigenic mineral phase.

Calcium (Ca) is normally present in silicate minerals at about the 1 percent level, therefore its contribution to sediment composition from detrital silicate minerals is relatively minor. The main source of Ca in sediments is from $CaCO_3$ shell material contributed from marine life. In Halifax inlet Ca variations are almost entirely due to the presence of shell fragments. The sediments with greater proportions of sand and silt tend to have more shell fragments and more $CaCO_3$, thus higher Ca.

Magnesium (Mg) is present in silicate minerals at concentrations that range from less than 1 percent to as high as a few tens of percent. In detrital silicate sediments the Mg content is usually associated with certain phyllosilicates such as chlorites. Mg is also present in sedimentary rocks, such as dolomites and magnesium carbonates. In Halifax inlet most Mg is expected to be associated with the clay minerals and would therefore be expected to be most abundant in the fine-grained fractions.

Potassium (K) is a common element in feldspars, clay minerals and zeolites. It is therefore associated with the non-carbonate minerals in sediments. The more specific common mineral associations are with the mica group of clay minerals and with the K-feldspars. In sediments from Halifax inlet the variations in K content are strongly associated with the Al variations, indicating that both the clay minerals and the feldspars contribute to the K content in the sediments.

Titanium (Ti) occurs as a major constituent in a few heavy minerals commonly found in sediments, but it also occurs as a replacement for Fe and Al in a number of sites in phyllosilicates, particularly mica types. It is this ability to substitute for other similar elements that accounts for most of its abundance in common sedimentary deposits. In Halifax inlet Ti probably occurs in some heavy minerals, but this is likely a relatively insignificant contribution to the total sediment composition. The amount of Ti can thus often be used as an index of the total phyllosilicate content in the sediments.

Iron (Fe) can be combined with a wide variety of anions to form complexes and minerals. Common mineral forms are as silicates (particularly phyllosilicates such as chlorites and biotites), oxides, sulfides, and phosphates. Iron is commonly a substitution element for a number of other elements, such as Ti, Si and Mg. Iron also changes its oxidation state readily under a variety of natural environmental conditions such as changes in the amount of oxygen and the pH conditions in aqueous phases. The form of this element in sediments thus provides useful information on the present and past depositional and environmental conditions. Because this element may exist in several different mineral phases in any sediment it is possible that as much as 10 percent of the total Fe may have been precipitated in the sediments after deposition of the detrital minerals. The source of this additional Fe may be from decomposing organic matter, from direct precipitation from the water, or from contaminants added to sediments as a result of industrial activity. In Halifax inlet Fe

concentration increases generally in the sediments with the highest proportion of fine-grained sediments (Buckley *et al.*, 1989). Until further chemical tests are conducted it will not be possible to determine if this trend is entirely due to changes in clay mineral content, or adsorption of Fe on the clays, or precipitation of some authigenic mineral phase.

Manganese (Mn) has some geochemical properties similar to Fe. There are two common oxidation states for Mn in sediments that are determined by natural environmental conditions. Mn is considered to be a trace element in the lattice structure of most silicates, but it may occur as a minor or major element in carbonates and oxides. In reducing marine sediments Mn is often dissolved into the pore water below the sediment surface, where it can diffuse up to the oxidized sediment interface, and be precipitated as an oxide or oxyhydroxide (Buckley and Cranston, 1988). In strongly reduced sediments there may be no oxidized surface layer, in which case the reduced Mn may be released directly into the overlying water column. The concentration of total Mn in coastal marine sediments varies over a relatively narrow range, usually between 300 and 1000 ppm. In Halifax inlet there is a complex relationship between the concentration of total Mn and the texture of the sediments, the organic matter content, and the redox state of the sediments. These relationships will not be clearly resolved until specific chemical tests are done to determine the various forms in which the Mn is being held.

Copper (Cu) occurs usually as a trace element in silicates, but may precipitate as a major element in some specific sulfides and oxides. This element also complexes readily with various organic compounds. In most marine sediments copper is present at trace element levels of concentration, well below 100 ppm. Sources of contamination in natural sediments are often related to mining wastes, industrial metal manufacturing and processing, as a corrosion product, or as a result of extensive use of anti-fouling paints in marine areas. Copper is also often associated with sewage sludge where it is most likely complexed with a variety of organic compounds.

Zinc (Zn) occurs as a trace constituent in a number of silicate minerals, but is a major component in a few economic sufide mineral deposits. This metal also occurs in some oxides, carbonates and phosphates. Zinc is not readily solubilized from most sulfides and is usually incorporated in sediments by adsorption on the finest particles or complexes with organic matter in the sediments. The normal range of concentrations of Zn in coastal marine sediments with average 1 percent organic carbon is between 100 and 150 ppm. These concentrations will be somewhat lower for sandy sediments and somewhat higher for sediments containing abundant organic matter. Sources of contamination of Zn in natural coastal sediments are commonly from adjacent mining operations and as a waste product from manufacturing and metal processing industries. Zn is also a corrosion product from some galvanized metals.

Nickel (Ni) is a transition metal having some geochemical characteristics similar to Zn. It is a trace element in some silicate minerals, forms oxides, and occurs in sulfide minerals as an economic deposit. It is quite insoluble and readily adsorbs on fine clays and organic matter. The normal concentration of Ni in coastal marine sediments is less than 60 ppm. Sources of contamination are metal manufacturing or processing plants and as waste products from hydrocarbon processing and lubricant disposal.

Lead (Pb) is a heavy metal that occurs in nature mainly as a lead sulfide. This metal is extremely insoluble and is readily adsorbed by organic matter, especially in reducing conditions. In uncontaminated coastal marine sediments the concentration of lead is seldom greater than 50 ppm, and is often less than 25 ppm. Sources of environmental contamination are from mining, smelting and reprocessing operations and as combustion product of lead additives in gasolines. Lead has also been used in a variety of paints and is a common constituent in municipal and industrial wastes.

Mercury (Hg) commonly occurs as a mercuric sulfide ore. The extreme insolubility of mercuric sulfide and most oxide forms of mercury indicates that this metal should not be transported in solution to any great extent. Mercury is also strongly adsorbed and complexed by particulate matter and organic compounds, and this may be the main mechanism for transport through natural systems. In reduced marine sediments

Hg is most likely present in a sulfide form and would likely remain quite immobilized. Under persistent oxidizing conditions some mercury in the sediments may be converted to a higher proportion of organo-mercury complexes, which increases the bioavailibility of the metal (Lu and Chen, 1977). Coastal marine sediments from uncontaminated areas contain Hg at levels generally less than 0.5 ppm. A common source of contamination is from municipal sewage, in which case it is thought that mercury is derived, in part, from commercial cleaning agents. Industrial releases of mercury in the past have been linked to production of chlor-alkali chemicals (Cranston and Buckley, 1972).

Lithium (Li) is a minor alkali element that occurs in a number of silicate minerals, but most commonly in the phyllosilicates, particularly the mica group. The strong association of this element with the clay minerals in marine sediments makes it an ideal element on which to normalize many of the other elements in order to determine which elements have similar affinities (Buckley and Cranston, 1989). Data provided in Buckley *et al.* (1989) may be used for this purpose, but this technique will not be discussed in this report.

Organic carbon (OC) in uncontaminated marine sediments originates predominantly from phytoplankton production, added directly as debris from microalgal blooms that settle to the bottom, or as products from grazing by herbivorous micro- and macrozooplankton in the water column. Benthic fauna in the sediment may filter particles from suspension and enrich surface sediments with egested organic carbon. Deposit feeding species also rework sediments by ingesting at depth and depositing fecal material at the surface or visa versa. Sulfur oxidizing chemoautotrophic bacteria that fix dissolved CO_2 may also produce organic carbon at depth horizons in the sediment that form the boundaries between oxic and anoxic layers. Kepkay and Novitsky (1980) attributed a peak in organic carbon accumulation at 40 cm depth in sediments from a station near Eastern Passage in Halifax inlet to this process.

Sewage discharge in urban coastal areas may enhance the natural sources of trace metal and organic carbon supplies. Bacteria utilize the organic matter and mineralize inorganic elements at rates determined by the amounts and types of substrates. These microbial processes oxidize organic carbon and create the characteristic redox conditions discussed above (Table 1). The simultaneous measurement of organic carbon and Eh gives information on the potential pathways of bacterial metabolism. Although distributions of organic carbon and trace metal concentrations in sediments do not indicate the magnitude of rates or pathways of supply, spatial patterns can be used to map areas of accumulation.

The distribution of organic carbon is also useful for interpretation of trace metal concentrations since many metals form organic complexes that minimize solubilization and diffusion across the sediment-water interface. Associations of trace metals with organic matter may also enhance their availability to benthic fauna that ingest and rework surface sediments.

Regional Variability of Sedimentary Geochemical Characteristics

Data compiled in the Buckley *et al.* (1989) report are based on the analyses of sediment samples collected from all regions of Halifax inlet, including Bedford Basin, the harbour waterfronts, Northwest Arm, and the Approaches to Halifax Harbour. These data are discussed here with reference to the sedimentary characteristics and the geochemical nature of sediments in each of these regions. Particular emphasis will be placed on discussion of the distribution of environmentally sensitive metals, Cu, Zn, Ni, Pb, and Hg in relation to Eh and organic carbon.

Sediment Texture

One of the basic sedimentary properties that greatly influences the geochemical characteristics of the bottom sediments is the texture (grain size distribution). Sediments dominated by fine grained particles (mud) usually have a greater capacity to adsorb minor trace elements than do sediments with a large percentage of sand or coarser material. Also fine-grained muds tend to have higher percentages of organic matter than sands and gravels. Because of the common association of metals with organic matter, the organically rich sediments also contain higher concentrations of most metals.

The percentage of clay (less than 0.004mm), and percentage of silt (0.004 to 0.06mm size) were combined to give the percentage of mud. This quantity was posted on the 1:25,000 scale map of Halifax inlet and values were contoured. From this illustration (Map 1) it may be seen that large areas of significant mud content exist throughout the regions of Halifax inlet. Approximately 80 percent of the seafloor of Bedford Basin is covered with sediment consisting of more than 60% mud. Nearly all of the bottom of Bedford Bay (adjacent to the Town of Bedford) in water depth greater than 10 m is covered with more than 60% mud. Sediments with more than 80% mud extend southeast from Mill Cove through the deeper parts of the passage between Western Ledges and Admiral Cove at the entrance to Bedford Bay. This area of high mud content broadens in Bedford Basin and covers nearly all of the floor in water depths greater than 40 m. An exception to this characteristic is a band of coarser grained sediments located midway between the Rockingham shore and Navy Island in water depths ranging from 35 m to 65 m. This sediment is thought to have been deposited from waste sediment and rock disposal that may have taken place a number of years ago. Evidence of sediment disturbance due to dumping can be seen on side scan sonar records of this area, (Fader, G., personal communication).

In The Narrows area of the harbour front the mud content decreases to less than 50%. Only one relatively small area of 60% mud exists in the centre of the harbour channel adjacent to the Halifax-Dartmouth Industries dry dock facilities. In the wider section of the harbour between Dartmouth Cove and the Queens Wharves in Halifax, mud contents increase to more than 80%. Also a broad area of high mud content extends along the central and eastern part of the harbour from near the Queen's Wharves , east of Georges Island into the northern part of Eastern Passage. Another broad area of high mud content exists between northern McNabs Island and Point Pleasant Park.

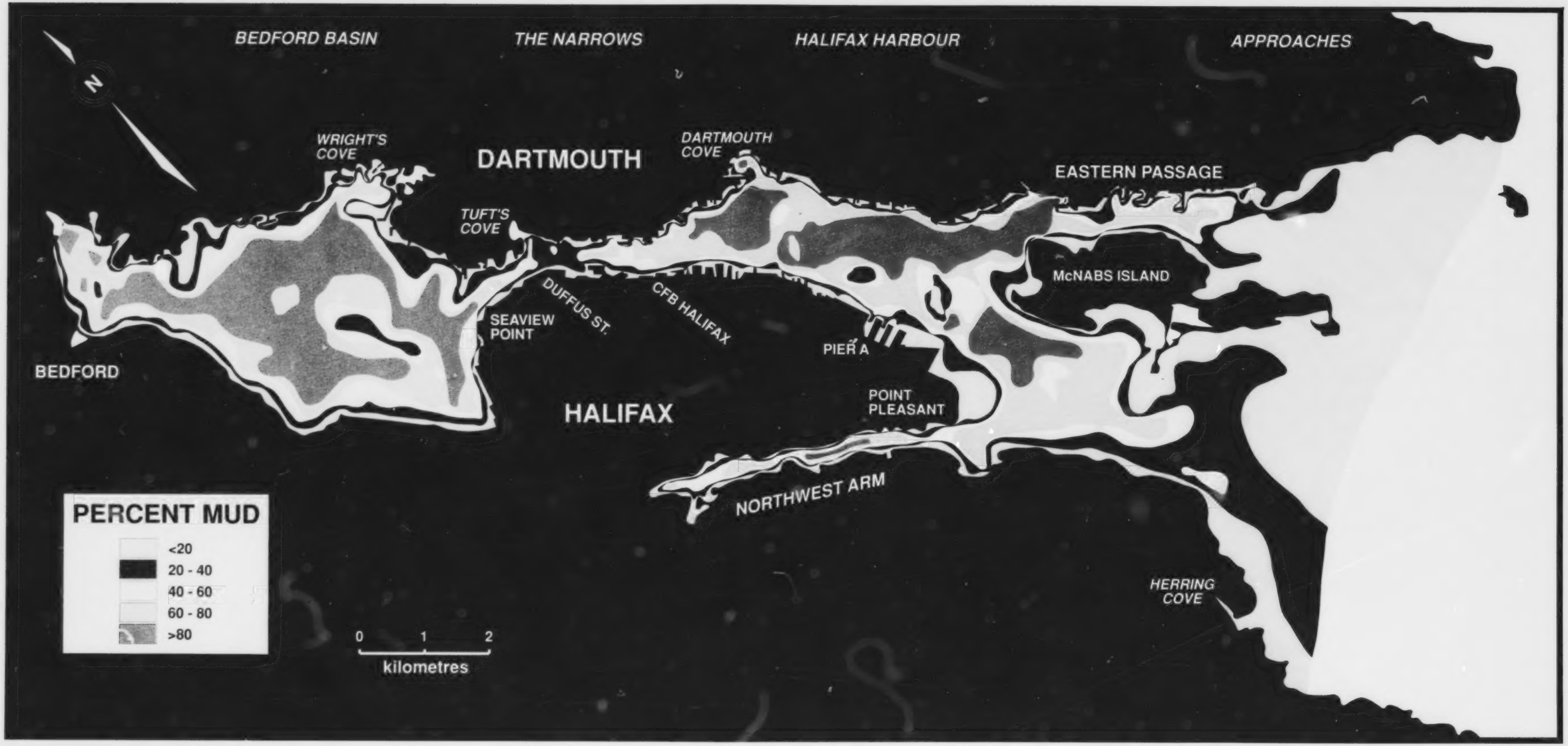
The central channel of the Northwest Arm contains relatively high mud content with pockets of mud exceeding 80% in the area southeast of the Dingle. Most of the rest of the Arm contains between 40 and 60% mud in the bottom sediments. The Approaches to Halifax Harbour south of York Redoubt and Maugher Beach contains very little mud, consisting mainly of sand and gravel.

Redox Potentials

The pattern of low Eh potential ($< +100$ mv) throughout Bedford Basin, The Narrows, Halifax Harbour and the Northwest Arm in samples collected in 1986 (Prouse and Hargrave, 1987) was also observed in the samples collected in 1988 (Table 1-2).

The sediments were grey to black in colour and smelled of hydrogen sulfide. The lowest Eh values in the 1986 survey (-181 mv) occurred in Halifax Harbour off Imperoyal. In the present study potentials near Mill Cove (-115 mv), in Wrights Cove (-134 mv), Tufts Cove (-196 mv), CFB Halifax (-259 mv), along the Halifax waterfront (-92 to -138 mv), Darmouth Cove (-144 mv) and off the Eastern Passage sewage treatment plant (-117 mv) are indicative of highly reduced sediments. Values are not as low (-4 to +94 mv) in the Northwest Arm. All of these locations, close to sewage discharges, have lower Eh values than sediments taken in central Bedford Basin near the Compass Buoy (1986- +69 mv, 1988- +193 mv) or the average calculated for all stations in Bedford Basin (+76 mv).

The highest Eh values measured in both 1986 and 1988 occurred at stations in the Harbour approaches (Table 1-2) indicative of oxygenated conditions expected from tidal exchange. Samples from nine stations near Tribune Head have values $> +200$ mv indicative of oxidized sediments. Kepkay (1980) also recorded a positive potential (+188 mv) in ponded muddy sediments at 40 m depth at the entrance to Eastern Passage. However, the grouped data for the outer Harbour shows a large range of potentials (+275 to -154 mv) possibly due to irregular bottom topography where fine grained sediment accumulate in depressions. Redox potentials immediately off the Tribune Head outfall (30-50 m offshore) (+290 and +295 mv) are among the highest recorded in 1988. Values within muddy sediment in Herring Cove (-5 and +43 mv) are lower as would be expected from reduced pore water exchange and higher organic carbon content in these deposits.


BEDFORD BASIN
THE NARROWS
HALIFAX HARBOUR
APPROACHES
N
WRIGHT'S COVE
DARTMOUTH
DARTMOUTH COVE
EASTERN PASSAGE
TUFT'S COVE
DUFFUS ST.
CFB HALIFAX
SEAVIEW POINT
McNABS ISLAND
PIER A
BEDFORD
HALIFAX
POINT PLEASANT
NORTHWEST ARM
HERRING COVE
PERCENT MUD
<20
20 - 40
40 - 60
60 - 80
>80
0 1 2
kilometres

Copper

Variations in Cu concentrations (Map 2) in the bottom sediments of Bedford Basin are generally associated with variations in sediment texture and with organic carbon content. There are four areas with abnormally high copper concentrations. The area immediately adjacent to the town of Bedford in the Mill Cove area contains muds with Cu concentrations up to 279 ppm. The concentration of this metal in sediments 1 to 2 km distant from Mill Cove had 1/3 to 1/5 of this concentration. In Bedford Basin three other areas contain elevated Cu levels. One isolated area in the north central part of the Basin, in a water depth of more than 60 m, contained the highest level of Cu (1913 ppm) measured anywhere in Halifax inlet. This extreme value is not thought to be an analytical artifact, because similar high concentrations were also found for other metals, including Pb and Zn. But no such anomaly was found for Hg results. It would thus appear that these unusual concentrations may have resulted from some type of inorganic waste dumped at this site.

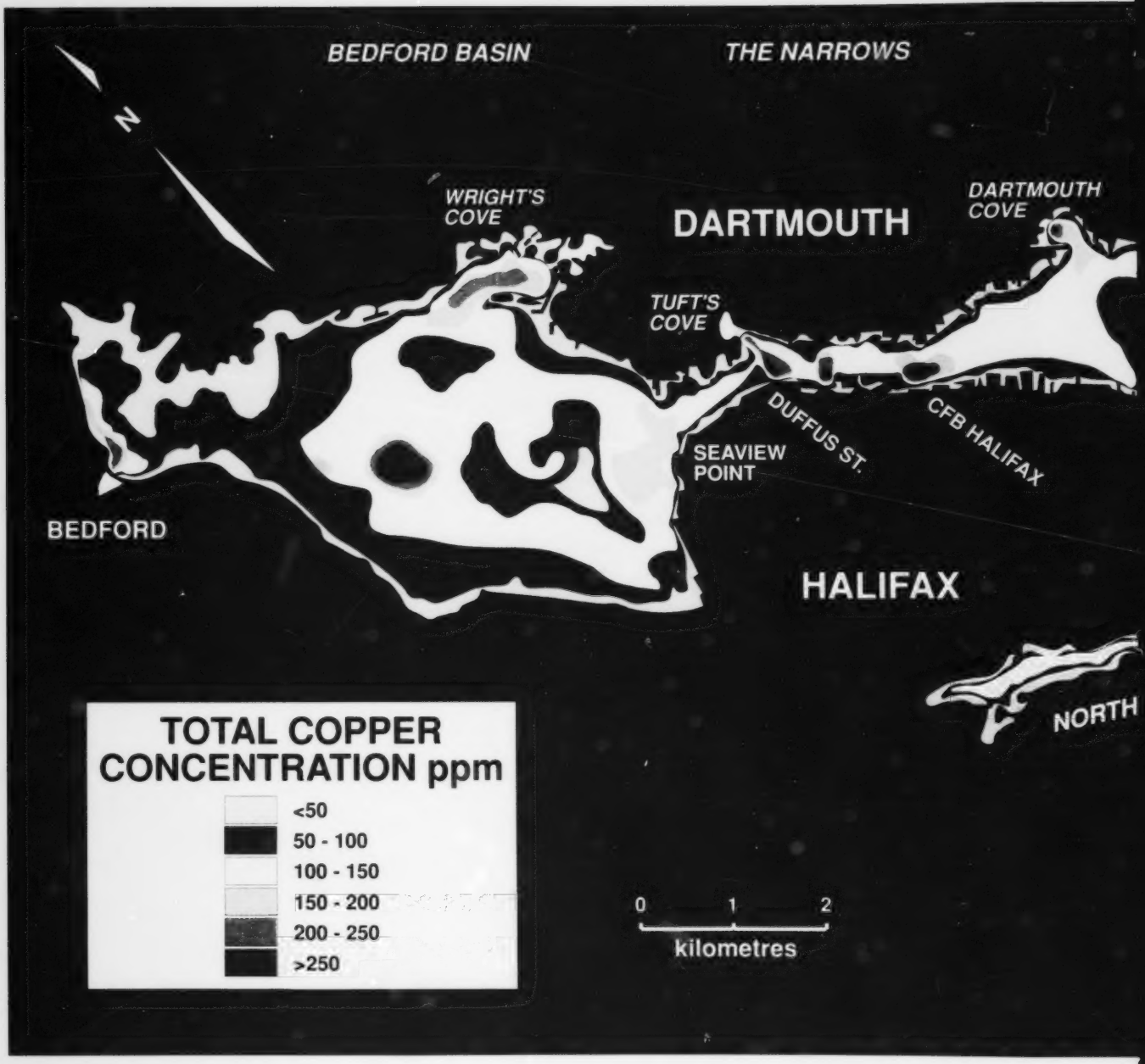
Another area of generally high Cu concentrations is located in Wrights Cove just east of Navy Island. The level of Cu concentration rose to 221 ppm in one sample from this area. This anomaly may be influenced by the fine organic-rich muds that have accumulated here adjacent to some sewage outfalls. Another notable Cu anomaly exists off the north and northwestern shore of Seaview Point. This anomaly is defined by a number of samples, three of which contain Cu in excess of 150 ppm. This nearshore zone appears to be related to the proximity of the previous city dump and landfill site.

Three local Cu anomalies are found in The Narrows section between the MacKay Bridge and the MacDonald Bridge. One of these is centred at the Duffus Street sewage outfall and extends across the harbour into Tufts Cove. The high concentration on the Halifax side of the harbour is 377 ppm, while that on the Dartmouth side is 459 ppm. This zone of contamination is most likely due to two sources; one from the Duffus Street outfall, the other due to several outfalls in the Tufts Cove area. A second contamination source is centred off pier Number 6 with a high Cu concentration of 310 ppm. This anomaly extends out into the harbour channel for a

Table 1-2. Distribution of oxidation reduction potentials (Eh) in surface sediments collected by Van Veen grab at various stations throughout Halifax inlet during August 1988. Values in parentheses summarize data obtained in 1986 (Prouse and Hargrave 1987). SD = standard deviation

Station Location	Number of Samples	Mean Eh (mv)	Range (mv)	SD
Bedford Basin	39 (49)	+71 (+115)	-134 - +193 (-68) - (+317)	85 (65)
Narrows and Halifax Harbour	30 (30)	+39 (0)	-259 - +282 (-154) - (+168)	144 (93)
N.W. Arm	5 (4)	+24 (-96)	-50 - +94 (-112) - (-74)	55 (16)
Approaches to McNabs Lt.	17 (10)	+113 (+114)	-79 - +284 (-69) - (+383)	90 (137)
Eastern Passage from Imperoyal	12 (7)	-9 (-154)	-79 - +174 (-181) - (+164)	94 (117)
Outer Approaches	19* (4)	+215 (+142)	+22 - +396 (+15) - (+273)	81 (120)

* does not include two stations within Herring Cove (- 5 and +43 mv)


BEDFORD BASIN
THE NARROWS
N
WRIGHT'S COVE
DARTMOUTH
DARTMOUTH COVE
TUFT'S COVE
DUFFUS ST.
CFB HALIFAX
SEAVIEW POINT
BEDFORD
HALIFAX
NORTH
TOTAL COPPER CONCENTRATION ppm
<50
50 - 100
100 - 150
150 - 200
200 - 250
>250
0
1
2
kilometres

HALIFAX HARBOUR
APPROACHES
ARTMOUTH
OVE
EASTERN PASSAGE
McNABS ISLAND
LIFAX
PIER A
POINT
PLEASANT
NORTHWEST ARM
HERRING
COVE

distance of approximately 250 m. The third anomaly is centred off CFB Halifax and is marked by a Cu concentration of 322 ppm.

The concentration of Cu in Dartmouth Cove reaches a high value of 324 ppm in the near shore area. This anomaly extends into the harbour and along the Dartmouth shore for a distance of 500 m and is likely the result of several sewer outfalls discharged into Dartmouth Cove. On the Halifax side of the Harbour a Cu anomaly is centred on the north side of Pier A where a major sewage outfall area is located. The high concentration of Cu reaches 271 ppm in this location. This anomaly also extends northward toward the inner Harbour.

The high Cu concentrations in the Northwest Arm are centred on the outfall off the Point Pleasant Park. The peak concentration of Cu is 264 ppm. The concentrations in muds from the central axis of the Arm gradually decrease toward the head of the Arm to levels of about 130 ppm. The concentration paterns give no indication that Cu is exported in a large quantity from the Northwest Arm into the southern approaches to Halifax Harbour. There is also no indication of highly unusual concentrations of Cu in sediments from Eastern Passage or Herring Cove.

All of the anomalies of Cu found adjacent to point sources of sewer outfalls in Mill Cove, Tufts Cove, off Duffus Street, off CFB Halifax, in Dartmouth Cove, and off Point Pleasant are associated with sediments that were found to be strongly reducing. Redox potentials at these sites ranged from -4 mv to -259 mv. Under these conditions organic matter in the sediments would be oxidized by sulfate reduction and Cu would be complexed with sulfides or organic compounds. One notable exception to the relationship between Cu anomalies in reduced sediments adjacent to sewer outfalls is the anomaly near Pier No. 6 where the sediments are not strongly reduced (redox potential of +148 mv). This may indicate that the source of contamination has not been dominated by municipal sewage outfall, but may be more directly related to industrial releases of the metal.

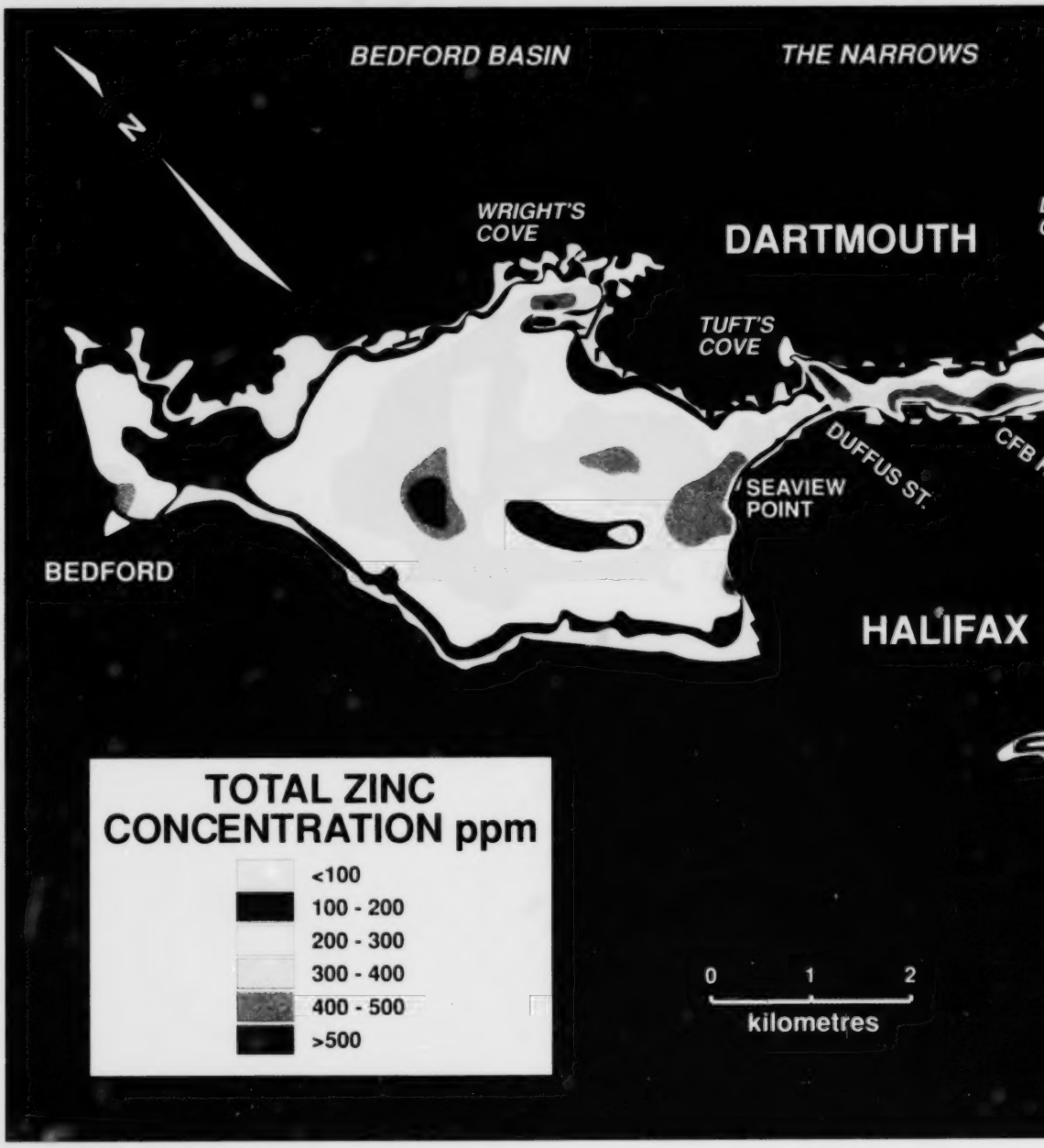
Zinc

The pattern of Zn concentrations in sediments throughout Halifax inlet (Map 3) is very similar to that of Cu. In Bedford Bay an anomaly of Zn is found in Mill Cove, adjacent to the town of Bedford (maximum concentration of 472 ppm) with diminishing concentrations extending out into the Bay for distances of 0.5 to 1.5 km. Zn concentrations are also elevated in Wright's Cove with one sample reaching 724 ppm. The previously noted anomaly of Cu in the north central part of Bedford Basin was also confirmed in the Zn results, in which the peak concentration was found to be 652 ppm, with an adjacent sample at 407 ppm. A broad anomaly of Zn was also found adjacent to Seaview Point where several samples contain more than 400 ppm. It is assumed that this anomaly is due to release of metal from the landfill site along this section of the Bedford Basin shoreline.

Anomalous concentrations of Zn exist in several large areas between the two bridges in The Narrows of Halifax Harbour. The high concentrations emanating from the Duffus Street outfall and Tufts Cove coalesce into one anomaly extending across the harbour. High concentrations of Zn reach 718 ppm at the entrance to Tufts Cove and 490 ppm off the Duffus Street outfall. A band of high Zn concentrations extends from off the Halifax-Dartmouth Industries dry-dock facilities, southward along the central channel to just north of the MacDonald Bridge. The southern part of this anomaly is centred on Zn concentrations as high as 696 ppm adjacent to CFB Halifax.

The concentration of Zn in the centre of Dartmouth Cove is between 539 and 555 ppm. The anomaly from this sewage outfall source extends outward in the harbour and northward along the Dartmouth water front for a distance of 800 m. On the Halifax side of the harbour at the Pier A outfall another anomaly of Zn concentration is defined by highest concentrations reaching 590 ppm. This anomaly is small in area, not extending much beyond the ends of the piers.

The anomaly of Zn near the Point Pleasant outfall is relatively weak compared with those near other outfalls in the Harbour. Peak concentrations of Zn are between 280 and 389 ppm. It also appears that the dispersion of Zn from this source is somewhat wider as compared with Cu, with some elevation of Zn extending out


BEDFORD BASIN
THE NARROWS
N
WRIGHT'S COVE
DARTMOUTH
TUFT'S COVE
DUFFUS ST.
SEAVIEW POINT
BEDFORD
HALIFAX
TOTAL ZINC CONCENTRATION ppm
<100
100 - 200
200 - 300
300 - 400
400 - 500
>500
0
1
2
kilometres

HALIFAX HARBOUR
APPROACHES
DARTMOUTH COVE
EASTERN PASSAGE
McNABS ISLAND
HALIFAX
PIER A
POINT PLEASANT
NORTHWEST ARM
HERRING COVE

into the harbour and approaches as far south as Fergusons Cove.

The dispersion of Zn from the various apparent point sources around the inlet suggests that Zn is slightly more mobile than Cu. The association of the highest Zn concentrations with sediments having the lowest redox potentials suggests that most of the Zn should be in a the form of rather insoluble sulfides. However, the affinity of Zn to adsorb on small particles or to complex with organics may allow this metal to be more widely dispersed.

Nickel

Because of the analytical difficulties in obtaining highly precise and accurate results for the analyses of Ni (Buckley *et al.*, 1989) it is not possible to clearly define anomalous areas of Ni concentrations. High concentrations were obtained for a number of samples scattered from off Point Pleasant Park, in Northwest Arm, along the western side of the Approaches to Halifax inlet, and around the Imperial Oil Refinery along the Dartmouth shore. Because these high concentrations have not been confirmed, and because there was no specific correlation with other geochemical variables, no meaningful interpretation of these results can be made. Determinations for labile Ni by selective leach analyses are currently underway.

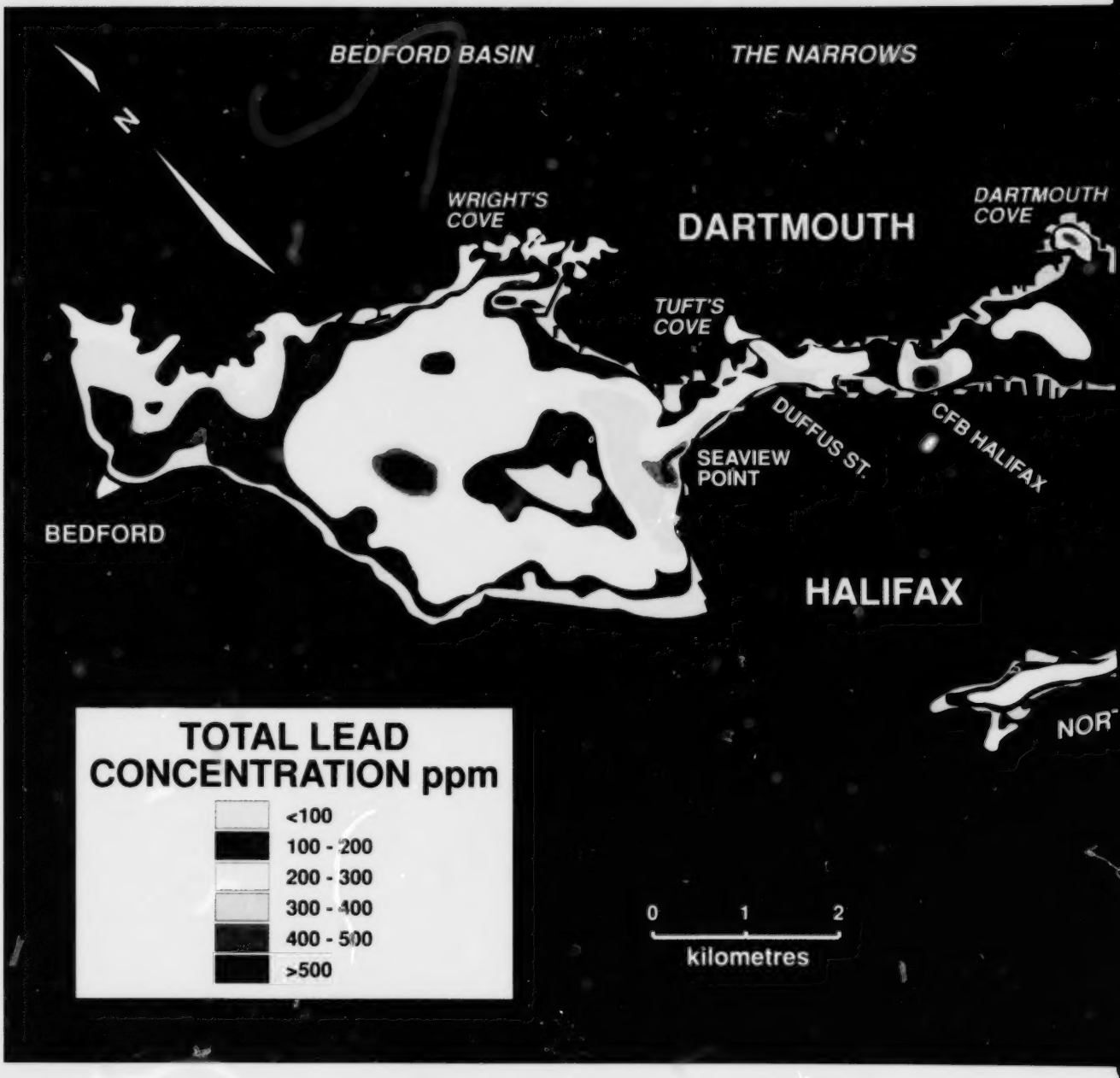
Lead

Pb concentrations in most of the sediments in the central part of Bedford Basin are elevated at least 8 times above normal levels for coastal marine sediments (Map 4). Superimposed on these generally high concentrations are three prominent anomalies. One sample taken in the centre of Wrights Cove contains 1442 ppm Pb, the highest found anywhere in the Halifax inlet. This isolated high value suggests a point source of contamination in the bottom mud. The second highest concentration (1237 ppm) is found in the north- central part of Bedford Basin where other metal analyses also showed a sharp anomaly. A broad anomaly extending from the container pier in Fairview Cove to an area adjacent to the Bedford Institute of Oceanography includes a sample near Seaview Point with a concentration of 344 ppm. This anomaly appears to be related to the possible leakage of lead from the former landfill site.

The coalescing anomalies in The Narrows section of the harbour between the Duffus Street outfall and Tufts Cove is defined by four samples all exceeding 300 ppm. The highest concentration (432 ppm) is on the Tufts Cove side. The most intense anomaly in the harbour waterfront area is found off CFB Halifax where one sample contained 696 ppm Pb. The sediments in this area are also the most strongly reduced, with a redox measurement of -259 mv. These data suggest that most of the lead in this sample would be in the highly insoluble sulfide form. The anomaly at Dartmouth Cove includes two samples from the centre and northwest side of the cove where the concentrations are 475 and 486 ppm, respectively. These muds are also strongly reduced. On the Halifax side of the harbour at Pier A two small but intense Pb anomalies are found on both the north and south sides of the pier. The anomaly on the north side is more intense with a concentration of 723 ppm, while that on the south side contains a concentration maximum of 306 ppm.

Lead concentration in sediments from the Northwest Arm are not as high as some of the anomalies in the Harbour proper, or in Bedford Basin. The highest concentration of Pb is found in the north branch of the Horseshoe, at the head of the Northwest Arm. Other samples in the Arm contain concentrations ranging from 147 to 282 ppm. The somewhat diffuse anomaly around the highest concentration at the head of the Arm rather than near the Point Pleasant outfall may suggest several different sources of the lead contamination in these sediments. Some Pb may have been contributed from older outfalls along the Arm which are no longer active or from motor vehicles along the Arm.

The abrupt decrease in lead concentration in sediments south of Point Pleasant Park and the Imperial Oil Refinery (on the Dartmouth side) suggest that Pb is not being transported out of the Harbour to any great extent. This observation holds in spite of the fact that several areas of high mud content exist in the southern approaches to the harbour near McNabs Island and in Eastern Passage. Lead concentrations in all these areas are less than 100 ppm. This observation would tend to support the suggestion that most of the Pb is highly insoluble and held in the reduced sediments in the Harbour and Bedford Basin.


BEDFORD BASIN
THE NARROWS
N
WRIGHT'S COVE
DARTMOUTH
DARTMOUTH COVE
TUFT'S COVE
DUFFUS ST.
CFB HALIFAX
SEAVIEW POINT
BEDFORD
HALIFAX
NOR
TOTAL LEAD CONCENTRATION ppm
<100
100 - 200
200 - 300
300 - 400
400 - 500
>500
0
1
2
kilometres

HALIFAX HARBOUR
APPROACHES
RTMOUTH
VE
EASTERN PASSAGE
McNABS ISLAND
IFAX
PIER A
POINT
PLEASANT
NORTHWEST ARM
HERRING
COVE

Mercury

The Hg distribution defines several anomalies indicative of point sources of contamination (Map 5). A small intense anomaly (2.19 ppm) is centred near the town of Bedford in Mill Cove. This anomaly extends less than 300 m out into Bedford Bay from the shoreline. Several other areas in Bedford Basin contain elevated levels of Hg, such as in Wrights Cove (1.65 ppm) and in the centre of Bedford Basin (1.51 and 1.78 ppm). Three other samples from the margins of Bedford Basin also contained elevated concentrations; one near the north end of Navy Island (1.78 ppm), one NW of the Bedford Institute of Oceanography (3.02 ppm), and one north of Seaview Point (1.65 ppm). The only clearly defined associations between Hg distribution and other metal contaminants is in Wrights Cove where Pb and Zn are also anomalous, and in the sample taken from the area NW of BIO where Pb was also found to be unusually high.

In The Narrows section of the harbour three clearly defined Hg anomalies can be identified. The Tufts Cove and Duffus Street outfall anomalies again converge to some extent. The concentration off the Duffus Street outfall is somewhat higher at 2.63 ppm, while the concentrations around Tufts Cove range from 1.53 to 1.87 ppm. An anomaly in the channel off the Halifax-Dartmouth Industries floating dry dock is defined by concentrations between 1.71 and 2.19 ppm. Further to the south an intense anomaly at peak concentration of 4.17 ppm is located off CFB Halifax. Part of this anomaly extends northward along the central channel of the harbour.

The Dartmouth Cove anomaly is defined by three samples all over 2.0 ppm Hg, with the highest concentration reaching 3.18 ppm. The extreme anomaly for Hg in the entire inlet is located around the Pier A site. The maximum concentration of 10.58 ppm is the highest concentration measured by this laboratory for any marine sediments in eastern Canada. The anomaly extends to both sides of Pier A and out into the channel between Georges Island and Halifax. It also extends northward along this channel to a sample taken about 200 m north of Georges Island.

A distinct anomaly of Hg concentrations occurs in the Northwest Arm adjacent to the Point Pleasant sewer outfall. The maximum concentration of Hg reaches 3.10 ppm. A gradual decrease in Hg contamination extends up into the Arm with values falling below 1.5 ppm about midway up the Arm in the central channel. There is little indication that much Hg is flushed out of the Northwest Arm and deposited in the entrance to the harbour proper. Levels of Hg in the sandy sediments in the approaches to the harbour are generally below 0.5 ppm.

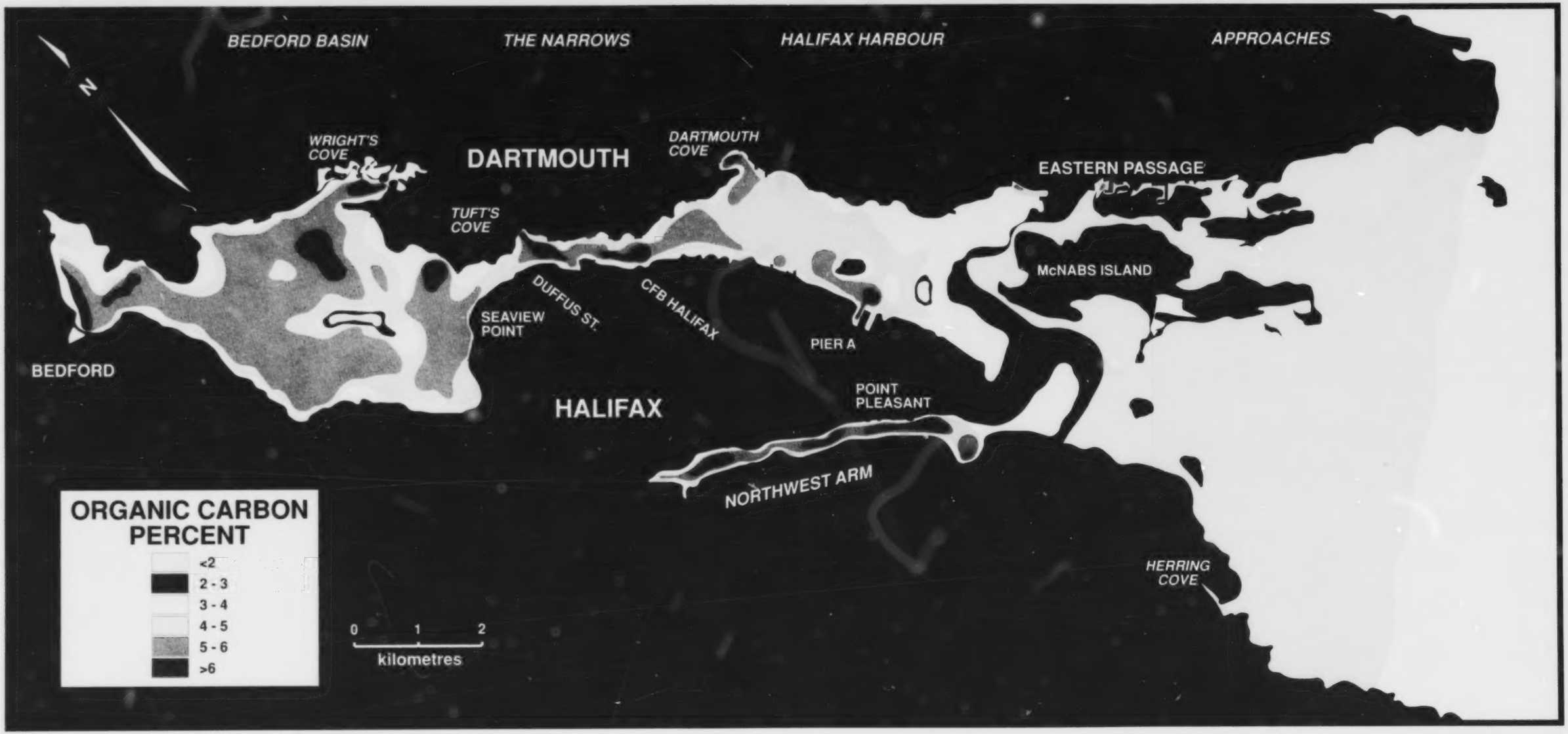
Organic Carbon

The distribution of organic carbon (Map 6) is based on concentrations presented in Buckley *et al.* (1989). Values for total carbon are slightly higher but they show virtually the same distribution pattern in the harbour and Bedford Basin.

Variance between replicate determinations of organic carbon in surface sediments was determined by analyses of differences between 10 subsamples from within one grab and between 10 grabs taken at two stations (A-Bedford Basin Compass Bouy and B-off McNabs Island in the Harbour approaches) (Prouse and Hargrave, 1987). Coefficients of determination were low (7.5 and 9.8%, respectively) for between and within grab measurements at station A where muddy sediments with a low sand content (16%) were texturally uniform. In contrast, higher variation (43.9 and 19.2%) occurred at station B where sand amounted to 45% of sediment weight. The non-homogeneous distribution of organic carbon at this station probably arises from the variability in amounts of fine organic matter mixed with coarser inorganic particles when small subsamples are taken for elemental analyses.

The overall concentrations of organic carbon in Halifax inlet sediments are considerably higher than those found in most coastal estuarine systems. Concentrations of OC in settled material collected in sediment traps over one year at various depths in Bedford Basin ranged from 3-16% with lower values (<5%) during winter months (Hargrave *et al.*, 1976). Levels in Bedford Basin sediments are mostly above 5.0% with anomalous values above 6%. In Bedford Bay a

BEDFORD BASIN
THE NARROWS
HALIFAX HARBOUR
APPROACHES
N
WRIGHT'S COVE
DARTMOUTH
DARTMOUTH COVE
EASTERN PASSAGE
TUFT'S COVE
McNABS ISLAND
DUFFUS ST.
CFB HALIFAX
SEAVIEW POINT
PIER A
BEDFORD
POINT PLEASANT
HALIFAX
NORTHWEST ARM
HERRING COVE
TOTAL MERCURY CONCENTRATION ppm
<0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
>2.50
0 1 2
kilometres


BEDFORD BASIN
THE NARROWS
HALIFAX HARBOUR
APPROACHES
N
WRIGHT'S COVE
DARTMOUTH
DARTMOUTH COVE
EASTERN PASSAGE
TUFT'S COVE
McNABS ISLAND
DUFFUS ST.
CFB HALIFAX
SEAVIEW POINT
PIER A
BEDFORD
HALIFAX
POINT PLEASANT
NORTHWEST ARM
HERRING COVE
ORGANIC CARBON PERCENT
<2
2 - 3
3 - 4
4 - 5
5 - 6
>6
0 1 2
kilometres

number of samples near and to the northeast and southeast of Mill Cove exceed 6% with the highest concentration near the town of Bedford reaching (7.33%). Anomalies in Bedford Basin are located in Wrights Cove (up to 6.41%), in the central part of the Basin (up to 6.59%), and northwest of the Bedford Institute of Oceanography (7.35%).

An earlier study (Hargrave and Kamp Nielsen 1978) showed that sedimentary organic carbon in Bedford Basin was inversely correlated with the gradient of bottom slope. Resuspension could cause downslope movement and accumulation of organically rich sediment particles at the base of steep slopes and in depressions in areas of irregular bottom topography. Organic carbon increased to levels >4% at depths below 18 m when bottom slope decreased. There is no significant correlation with water depth and sediment organic carbon in Bedford Basin for samples collected in 1988. The lowest values (2.04 and 2.70%) are in Bedford Bay but concentrations elsewhere in the Basin range up to 7.33% with the maximum located off Mill Cove as mentioned above. The average concentration for organic carbon at all stations in 1988 (n=33) is 5.01% (sd = 1.09%). The corresponding value for samples collected in 1986 (n=49) is 4.79% (sd = 1.09%).

In The Narrows section of the Harbour two anomalies in organic carbon are evident. One represents sources from the Duffus Street and the Tufts Cove outfalls. Concentrations near the former site range from 6.51 to 9.85 % with values at the entrance to Tufts Cove up to 15.85%. The second distinct anomaly (7.23%) is located off CFB Halifax.

In Dartmouth Cove the highest organic carbon concentration is in sediments from the centre of the cove (8.71%). The anomaly around Pier A, the second highest in the inlet (maximum of 11.96%), extends out beyond the pier and northward along the channel to the west of Georges Island.

The generally high organic carbon content of the muds in the Northwest Arm are highest at the Point Pleasant outfall area (8.22 and 10.06%). The most obvious association of organic carbon in this area is with the high percentage of mud in the bottom sediment. For this reason anomalous concentrations are found in the broader sections of the Arm southeast and northwest of the Dingle.

Organic carbon concentrations above 2% extend out into the approaches to the harbour as far as Fergusons Cove on the west and as far as Lawlor Island through Eastern Passage. A few isolated high values occur along the Eastern Passage shore, at Eisner Cove and at the Autoport perhaps reflecting discharge from the Eastern Passage sewage treatment plant.

Sediments in the Harbour approaches are coarse grained. Exceptions occur in Herring Cove where one station within the Cove contained high organic carbon (4.08%) and off Sandwich Point where three stations along an offshore transect decreased from 2.06% to 0.27%. The average (± sd) concentration for organic carbon was 0.63% (0.67%) (n = 21) for stations in the Harbour approaches outside of McNabs Light. Bathymetry in this area is complex and a depression off of Sandwich Point may serve to trap fine sediments. Mud content at the most shoreward station (43%) decreased greatly (to 4.5%) with distance offshore.

Sediment Oxygen Uptake and Dissolved CO_2 in Pore Water

Measurements of sediment oxygen uptake reported in Prouse and Hargrave (1987) did not separate biological (respiration) and chemical oxygen uptake for samples collected at 102 stations throughout Halifax inlet. Values varied over two orders of magnitude with highest rates (>200 μg $O_2 \cdot g^{-1} \cdot h^{-1}$) measured in central Bedford Basin, along the Dartmouth shore of Halifax Harbour and in the Northwest Arm (Table 1-3). These rates are an order of magnitude less than similar measurements made with settled particulate matter collected at various depths in Bedford Basin over one year (Hargrave *et al.*, 1976).

Highest rates of uptake measured in the present study for sediments from Bedford Basin (values >100 μg $O_2 \cdot g^{-1} \cdot h^{-1}$) occur off Mill Cove, Wrights Cove and Fairview Cove and throughout the central Basin at depths >20 m. Similar high rates appear throughout Halifax Harbour and the Northwest Arm. Generally lower rates in the Narrows and Harbour Approaches, where more coarse grained sediments are found, led to the conclusion in the earlier study that high oxygen demand in other areas reflected chemical uptake due to reduced inorganic sulfides accumulated in muddy sediments. Low rates of uptake (3-55 μg $O_2 \cdot g^{-1} \cdot h^{-1}$) near Tribune Head in 1988

are similar to the range observed in 1986 at three stations across the Harbour outside of McNabs Lighthouse (2-51 μg $O_2 \cdot g^{-1} \cdot h^{-1}$). Organic carbon is low at these stations (<2%) (discussed above) and presumably there is little accumulation of reduced sulfides to create a high oxygen demand.

Concentrations of total dissolved CO_2 in surface water from Halifax Harbour vary between 2.0 and 2.2 mM (45 to 52 ml CO_2 L^{-1}). Kepkay (1980) reported a concentration of 2.88 mM above the bottom at the entrance to Eastern Passage with a higher value (9.87 mM) 10 cm below the sediment surface. Concentrations in sediment pore water at all stations are greater than values in seawater due to production within surface sediment (Table 1-4).

The highest mean value (43.5 mM CO_2) occurs between Point Pleasant Park and McNabs Light. However, there was a high variance between stations throughout this area (CV = 52%). The average value for the central Harbour, although lower, is derived from a range of values equal in magnitude to those in the outer Harbour. Lowest concentrations are within Bedford Basin, but even here the CV is relatively large. Adjacent stations in Wrights Cove have concentrations (3.1 and 21 mM CO_2) that span the full range of values observed in Bedford Basin.

There is no clear relation between carbonate content in sediment and dissolved CO_2 in pore water. Carbonate accounts for <5% in the majority of samples with a few sites in the Narrows between 10 and 15%. The anomalies occur in the Harbour Approaches near Tribune Head (13.8 to 21.8%) and at one station near Devils Island (45.2%). The level of dissolved CO_2 in pore water at the latter station is one of the lowest recorded (3.69 mM), while those near Tribune Head are highly variable (3.14 to 42.13 mM) and not correlated with sediment carbonate content.

There is a trend for sites with negative Eh values to have elevated concentrations of dissolved CO_2 in pore water but the pattern was not consistent throughout all areas. For example, the low Eh values of -196 mv in Tufts Cove and -144 mv in Dartmouth Cove are associated with high CO_2 concentrations of 84 mM and 100 mM respectively, while the more highly reduced sediment off CFB Halifax (Eh -259 mv) contains only 9.1 mM. Sand content was higher (52%) at this site than in Dartmouth Cove which would be expected to lead to less accumulation of reduced compounds, lower rates of sulfate reduction and a corresponding reduction in pore water CO_2.

Even more surprising is the association of the maximum value for dissolved CO_2 measured in the Harbour Approaches off McNabs Island (101 mM) at a mid-channel location with an Eh value of +180 mv. Kepkay (1980) observed a gradient of increasing dissolved CO_2 down to 120 cm in a core from a station at the entrance to Eastern Passage. However, the concentration gradient over the upper 10 cm (2.88-9.87 mM) was not as large as that to the bottom of the core (maximum

Table 1-3. Oxygen uptake by surface sediment slurries stirred in aerated seawater from various stations in Halifax inlet collected in 1986 (Prouse and Hargrave 1987) and during October-November 1987 (*).

Station Location	Number of Samples	Mean Oxygen Uptake μg $O_2 \cdot g^{-1} \cdot h^{-1}$	Range	SD	CV (%)
Bedford Basin	19	218	102 - 125	132	61
Halifax Harbour	22	219	112 - 319	191	87
Northwest Arm	4	267	244 - 300	41	15
Harbour Approaches	13	47	2 - 78	34	72
Tribune Head (*)	6	19	7 - 32	13	68
Bell Bouy (*)	3	13	3 - 55	5	38

50.3 mM). All samples for our analyses of pore water CO_2, however, were taken from the surface centimetre. If steep concentration gradients were present, these would have been destroyed when the pore water was extracted by centrifugation.

There were also large horizontal concentration gradients between adjacent stations near Herring Cove with a wide range of values (3-42 mM) in sediments with Eh values between +160 and +300 mv. While these potentials and the low organic content discussed above indicate that reducing conditions were not present at the time of sampling, organic carbon supply could be high to maintain high levels of dissolved CO_2 in pore water.

Associations of Metal Concentrations with Percentages of Organic Carbon and Mud

In order to determine if there are correlations between metal concentrations and the amount of organic carbon or the amount of fine grained sediments in the samples, a series of statistical tests were conducted (Table 1-5).

Table 1-5 shows that the variation in the concentration of all these metals in 219 samples is significantly correlated with variations in the organic carbon content of the samples. In the case of Zn more than half of the variation can be related to variation in organic carbon content. Decreasing percentages of the variation in Hg, Pb and Cu can be accounted for by variations in the organic carbon content. For example, other factors account for 83% of the variation in the concentration of Cu in these samples. No significant correlation exists between the variation of these metals and the percentage of mud in the sediments. These correlations show that organic carbon content is not strongly related to the mud content of the samples. This is contrary to the normal relationship in most natural marine sediments.

These results suggest that other factors, such as redox potential, may be a more significant factor in determining the concentration of these metals in the bottom sediments. This possibility is confirmed by the observations made earlier that many of the high metal anomalies are found in sediments with low redox potentials. The pattern of low Eh potentials <100 mv throughout Bedford Basin, The Narrows, Halifax Harbour and the Northwest Arm is also reflected in the distribution of silt and clay and organic carbon. Sediments in all of these areas were usually grey to black in colour and smelled strongly of hydrogen sulfide. Metals in these deposits are probably present as insoluble sulfides.

Comparison of Contaminant Concentrations from Other Areas

Comparison of metal concentrations and other sedimentary properties between coastal

Table 1-4. Distribution of dissolved CO_2 in pore water from surface sediments (upper 1 cm) collected by Van Veen grab at various stations throughout Halifax inlet during August 1988. SD = standard deviation, CV = coefficient of variation (SD/mean) as a percentage. (*) Values do not include two stations within Herring Cove (35.9, 25.2 mM CO_2)

Station Location	Number of Samples	Mean CO_2 (mM)	Range (mM)	SD	CV (%)
Bedford Basin	39	7.4	3.1 - 21.1	3.6	48
Central Harbour	31	17.9	5.4 - 99.9	21.4	120
Northwest Arm	5	15.6	13.2 - 21.5	3.4	22
Outer Harbour to McNabs Lt.	17	43.5	10.5 - 101.5	22.5	52
Approaches outside McNabs Lt.	19 (*)	17.6	3.1 - 42.1	9.5	52

systems is difficult to make in a comprehensive sense. Similar sampling and analytical techniques may not have been used, sampling densities may be different, and data may be biased by concentration of sampling around contamination sites. Basic sedimentary properties (such as the texture) may differ greatly between coastal systems. In the following comparison of the results from Halifax inlet with those obtained in other coastal systems in eastern Canada, some of these difficulties may have been reduced, because the same basic analytical techniques were used in all of the studies.

Previous geochemical studies have been carried out in the LaHave River and Estuary system (Cranston and Buckley, 1972; Cranston *et al.*, 1975), in the Strait of Canso and Chedabucto Bay system (Buckley, 1973; Cranston *et al.*, 1974; Buckley *et al.*, 1974), and in the Miramichi River and Estuarine system (Winters *et al.*, 1978; Winters and Buckley, 1978; Willey and Fitzgerald, 1980; Buckley and Winters, 1983). In addition some data have been obtained from the open continental shelf off Nova Scotia, and serves as background for this environment, (Fitzgerald *et al.*, 1989). In all of these studies the same basic analytical techniques were used for the analysis of total metal content in the sediments, (Buckley and Cranston, 1971; Cranston and Buckley, 1972). Also the analytical technique for organic carbon has remained constant throughout these studies, (Cranston *et al.*, 1975). Data from intertidal sediments in Cobequid Bay at the upper end of the Bay of Fundy are also included for comparison (Loring, 1978; Hargrave and Neame, 1978).

Table 1-6 summarizes trace metal and OC data from all of the previous studies referred to above, and compares these results with those obtained from the Halifax inlet. Mean concentrations and the extremely high concentrations of OC, Zn, Cu, and Pb from Halifax inlet are all greater than values found in any of the other coastal systems. Only Hg in the Strait of Canso was found to have a mean concentration greater than that measured in Halifax inlet. However, the maximum concentration found in Halifax Harbour is greater than any concentration found in the other areas.

This relative difference between systems exists in spite of the fact that some of the other systems have well known sources of contamination. For example, the Strait of Canso area was subjected to severe contamination as a result of discharges from the wood pulp plant and adjacent heavy water plant operating in that area at the time of the geochemical survey, (Buckley *et al.*, 1974). The high mean concentration of Hg in

Table 1-5. Comparison of the variation in the concentration of the metals Cu, Zn, Pb and Hg with the variation in the OC and percent mud in surface sediment samples collected during August 1988 from Halifax inlet.

	Percent Organic Carbon			Percent Mud		
	r	r^2 (%)	p (%)	r	r^2 (%)	p (%)
Cu	0.412	17.0	99.99	0.131	1.7	94.4
Zn	0.765	58.6	99.99	0.182	3.3	99.3
Pb	0.595	35.4	99.99	0.123	1.5	92.8
Hg	0.678	46.0	99.99	0.112	1.2	89.7

Note: r^2 is expressed as the percentage of the variance in the concentration of the metal that can be accounted for by the covariance of the organic carbon or mud content. The probability, p, that the correlation is significant is expressed in percentage probability. Percentages below 99.9 are not highly significant.

sediments from the Canso Strait indicates that some release of Hg had taken place, probably as a biproduct of the pulp industry. The relatively high concentration of OC in the Miramichi system has been directly linked to the wood processing industries located in the upper estuary, (Buckley and Winters, 1983). The relatively high concentration of Zn in the Miramichi sediments has been linked to the discharge of mining wastes in the Miramichi River (Willey and Fitzgerald, 1980).

The enrichment of Zn, Cu, and OC in sediments from Halifax inlet compared with the sediments on the Scotian Shelf can also be seen in Table 1-6. The mean concentration of OC in Halifax inlet is about a factor of 4 times higher, while the enrichment for Zn and Cu is by factors of about 3 and 4.5 respectively.

It should be noted that direct comparison of texturally equivalent sediments from other coastal or shelf environments with the sediments in Halifax Harbour is not possible. For example, the silty muds from the basins on the Scotian Shelf have about 1% OC while the few texturally equivalent samples from Halifax Harbour have at least four times as much organic carbon.

Table 1-6. Comparative Concentrations of Organic Carbon and the Metals Zn, Cu, Pb, and Hg in Sediments from Coastal Marine Areas in Eastern Canada. (*) data from intertidal sediments summarized from Loring (1978) and Hargrave and Neame (1978)

Study Area	Organic Carbon (%)	Zn (ppm)	Cu (ppm)	Pb (ppm)	Hg (ppm)
Miramichi					
mean ± SD	3.78 ± 2.57	198 ± 69	20.8 ± 10.6		0.13 ± 0.01
minimum	0.20	104	11		0.03
maximum	8.50	326	44		0.40
number	20	20	22		20
Canso					
mean ± SD	1.31 ± 1.37	89.9 ± 36.4	23.9 ± 8.6	62.9 ± 26.0	1.64 ± 1.18
minimum	0.07	10	10	25	0.10
maximum	9.30	310	53	120	4.10
number	95	95	95	95	95
LaHave					
mean ± SD	1.31 ± 1.63	60.0 ± 40.0	16.5 ± 18.7		0.79 ± 0.69
minimum	0.13	18	3.3		0.41
maximum	5.04	151	63.6		2.72
number	10	10	10		10
Cobequid Bay (*)					
mean ± SD	0.42 ± 0.25	59.0 ± 25	18 ± 7	18.8 ± 4.6	
minimum	0.06	23	8	14	
maximum	0.63	77	24	24	
number	4	4	4	4	
Scotian Shelf					
mean ± SD	0.95 ± 0.60	69.3 ± 34.8	19.5 ± 10.2		
minimum	0.43	36	9		
maximum	2.21	103	50		
number	8	8	8		
Halifax inlet					
mean ± SD	4.24 ± 2.24	229.7 ± 146	91.3 ± 130	161.2 ± 166	0.97 ± 1.00
minimum	0.16	27	2	16	0.01
maximum	12.53	726	1913	1442	10.58
number	140	259	259	259	240

Characterization of Contamination Sources in Halifax Inlet

Anomalous concentrations of sedimentary OC, Cu, Zn, Pb, and Hg have been identified as being associated with a number of contamination sources in Halifax inlet. It is possible to characterize these various sources based on the "signature" of the profile of relative concentrations of organic carbon and metals present as contaminants. This can be accomplished by comparing the enrichment of elements in sediments near contamination sources relative to the background, or with mean concentrations for the entire study area. In Table 1-7 the concentration ratios have been calculated using both the mean concentration expected for coastal marine sediments, and the mean concentration actually found in the Halifax inlet sediments.

Table 1-7 identifies 12 separate contamination areas adjacent to sewer outfalls, or other suspected contaminant sources. A single sample representing the maximum concentration of contaminants in the sediments at each anomaly was used to calculate the concentration ratios, using either the background or the mean value. From these data it is possible to group contamination sites on the basis of similar anomalies. This technique allows for an assessment of the relative impacts of different types of contamination sources.

Some contamination sites identified on the maps (Map 1-6) are adjacent to known sewer outfalls and these may be expected to reflect the general chemical nature of the material discharged. Outfalls located at Mill Cove near Bedford, off Duffus Street in The Narrows, in Dartmouth Cove, and off Point Pleasant Park in

Table 1-7. Concentration ratios relative to (A) background and (B) study area mean. Sample identifications by letter and number refer to station locations reported in Buckley *et al.* (1989).

Sample	A					B				
	OC	Cu	Zn	Pb	Hg	OC	Cu	Zn	Pb	Hg
C7 Mill Cove (Town of Bedford)	7.3	14.0	6.7	6.8	4.4	1.7	3.1	2.1	1.0	2.3
B19 Wrights Cove	6.4	11.1	10.3	57.7	2.8	1.5	2.4	3.2	8.9	1.4
B25 Centre of Bedford Basin	5.0	95.7	9.3	49.5	1.7	1.2	21.0	2.8	7.7	0.9
C31 Seaview Point (W)	5.3	7.9	6.0	23.3	1.8	1.2	1.7	1.8	3.6	0.9
C33 Seaview Point (E)	5.5	9.1	6.6	23.9	2.8	1.3	2.0	2.0	3.7	1.5
C35 Tufts Cove	15.9	23.0	10.3	17.3	3.7	3.7	5.0	3.1	2.7	1.9
C40 Duffus Street (outfall)	6.5	18.9	7.0	15.5	5.3	1.5	4.1	2.1	2.4	2.7
C46 Halifax-Dartmouth Industries (Shipyards)	5.5	15.5	6.6	8.5	2.8	1.3	3.4	2.0	1.3	1.4
C49 CFB Halifax	7.2	16.1	9.9	27.8	5.4	1.7	3.5	3.0	4.3	2.8
C51 Dartmouth Cove	8.7	16.2	7.7	19.0	6.4	2.1	3.5	2.3	2.9	3.3
C46 Pier A	12.0	13.6	8.4	28.9	21.2	2.8	3.0	2.6	4.5	10.9
C72 Point Pleasant - N.W. Arm (outfall)	10.1	11.0	5.6	11.3	4.5	2.4	2.4	1.7	1.7	2.3
Reference conc. (ppm)	1.0	20	70	25	0.5	4.24	91.3	229.7	161.2	0.97

the Northwest Arm all appear to have a chemical profile dominated by Cu enhancement more than any other metal (relative to the mean concentration for all sediments in the Halifax inlet). The second ranked metal in terms of enhancement is Hg, followed by Pb or Zn and the least enhanced element is organic carbon (with the exception of the Point Pleasant outfall). The enhancement profile is thus:

$$Cu > Hg > Pb \text{ or } Zn > OC$$

This profile appears to reflect source dominance of municipal or domestic sewage.

The second type of contamination anomaly is characterized by Pb dominance as exemplified by sites in Wrights Cove, off Seaview Point, and off CFB Halifax. The metals showing secondary enhancement are Zn or Cu followed by OC or Hg. The distinct features of this profile are the relatively high enhancements of Pb combined with the relatively low enrichments of Hg and OC. This profile is thought to represent significant chemical input from solid wastes and industrial chemicals, such as paint and anti-corrosive products. The enhancement profile is:

$$Pb > Zn \text{ or } Cu > OC \text{ or } Hg.$$

The final group of contamination sources is derived from mixed sources or is dominated by a specific contaminant in a matrix of sewage waste. Examples of these types are the anomalies in the north central Bedford Basin, the outfall area in Tufts Cove, the sediments off the Halifax-Dartmouth Industries Shipyards and the area around Pier A. The anomaly in the north central part of Bedford Basin (site B 25) is dominated by very high enrichment of Cu and Pb, but relatively minor enrichment of Hg. This anomaly appears to be caused by some specific waste concentration, possibly the disposal or loss of debris from ships. The Tufts Cove area is also enriched in Cu with significant secondary enrichment by Pb or organic carbon and with significant enrichment by Zn. This profile suggests contamination by industrial metal losses superimposed on sewage sludge waste. The high organic carbon enrichment is unique in that the texture of the sediments in this area is rather coarse. It is possible that some of this carbon enrichment is derived from tar residues derived from the electrical generating station at Tufts Cove.

The site off the Halifax Industries Dry Dock in The Narrows section of the Harbour is another example of a mixed chemical profile. The dominant metal is Cu followed by Zn or Pb and Hg. The relatively high ranking of Pb enhancement suggests contamination from industrial sources in the shipyard, possibly paints. The contamination around Pier A is dominated by enhancement of Hg and Pb. These two metals may be derived from different sources superimposed on the sewage sludge waste. The unusual high concentration of Hg suggests a specific contamination of Hg. The enhancement of Pb may be associated with Pb-based paints that have been widely used by marine vessels using these shipping terminals.

SUMMARY AND CONCLUSIONS

Sediments in Halifax Harbour, the Northwest Arm and Bedford Basin of Halifax inlet are contaminated with respect to the total concentration of organic carbon and the metals Cu, Zn, Pb, and Hg. The degree of contamination is greater than that observed for other coastal and estuarine sediments in eastern Canada. The mean concentration ratios of these elements over uncontaminated coastal marine sediment concentrations are by factors of 4.2 for organic carbon, 4.5 for Cu, 3.3 for Zn, 6.4 for Pb, and 2.0 for Hg. Most of these organic-rich sediments are in a state of strong chemical reduction with average Eh values $< +100$ mv indicating limited oxygen penetration into the sediments. For this reason most of the high concentrations of metals such as Zn, Pb and Hg are probably present as highly insoluble metal sulfides.

At least 12 major contamination areas can be identified by anomalous concentrations of organic carbon and the environmentally sensitive metals. These areas are associated with major sewer outfalls and with suspected industrial contamination. The dispersion of contaminants away from these source areas is reduced by the rapid adsorption or precipitation of the metals on sediments. The pattern of dispersion from several of the highly contaminated areas in the Harbour is north, into the Harbour. There appears to be limited export of the contaminants to open marine areas in the Approaches to Halifax inlet. Based on these sedimentary geochemical indications it appears that Halifax inlet is not well flushed with respect to the removal of

contaminated sediments from the inner harbour and Bedford Basin.

Additional chemical analyses and experiments are required to better define the chemical form in which metals are being held in the sediments and to measure their mobility into overlying water. It is also important to better identify the chemical nature of the organic matter contained in the sediments. This information would allow sources of contaminants to be traced and the potential reactivity of these sediments to be assessed. Additional metal analyses for Cd, Ni, and Cr will be required to improve the identification of contamination sources and the mechanisms of geochemical dispersion of metal contaminants. Important questions concerning the bioavailibility and environmental hazards of metals in the sediments and their impact on metabolic activities of micro- organisms and benthic fauna have yet to be answered.

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CHAPTER 2

BENTHIC BIOLOGICAL OBSERVATIONS

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ABSTRACT

Bottom photographs (approximately 1.0 m^2) along four nearshore transects (5 to 25 m depth) near Tribune Head on the western shore of the approaches to Halifax Harbour were used to determine macrophyte cover, sediment texture and the presence of invertebrates >2 cm in length. The area near Herring Cove is influenced by sewage discharge and the observations were intended to provide information on habitat quality. Van Veen grabs were taken to obtain surface sediment for organic carbon and oxidation reduction potential measurements reported in Chapter 1.

No anthropogenic debris was observed in the limited area photographed and there was no visible discoloration of surface sediment expected if sulfides accumulated through increased organic matter loading. Dense beds of macrophytes covered the steeply sloped rocky bottom at depths from 7 to 17 m with coarse sand at deeper depths.

Data summarizing benthic macrofauna species, abundance and wet weight biomass at seven stations in Bedford Basin obtained in an earlier study are tabulated and compared with similar data from other coastal areas of Nova Scotia. The highest biomass (844 $g \cdot m^{-2}$) in Bedford Basin near the Mill Cove sewage outfall was an order of magnitude greater than values at other stations (2 to 152 $g \cdot m^{-2}$) which were similar to those observed in other coastal embayments in eastern Canada.

INTRODUCTION

An underwater photographic survey in the vicinity of Herring Cove was undertaken during the fall of 1987. The observations were intended to provide a response to questions posed to the Habitat Management Branch, Department of Fisheries and Oceans, concerning marine habitat quality near Herring Cove due to sewage discharge from the Tribune Head outfall. Bottom photographs and sediment grab samples taken on October 5 and November 19, 1987 were used to characterize the benthic community and organic matter distribution in surface (upper 1 cm) sediments near Tribune Head. These observations were supplemented by photographs of bottom grabs taken during sediment sampling in August 1988 throughout Halifax inlet described in Chapter 1 of this report.

Unpublished data from an earlier study of benthic macrofauna distribution in Bedford Basin are included and compared to estimates of benthic biomass in other coastal areas in Nova Scotia.

SAMPLING METHODS

Two separate bottom photographic surveys were conducted (October 5 and November 11, 1987). Two Umel underwater cameras mounted in a stereo mode with a strobe system were triggered with a bottom contact switch to give bottom photographs with a coverage of approximately 1.0 m^2. Black and white film was loaded into one of the two 35 mm cameras and Ektachrome colour film was used in the other to provide pairs of photographs at each of 20 sites near Tribune Head (8), within Herring Cove (5), off Sandwich Point (3) and near Fergusons Cove (4) along the western shore of the approaches to Halifax Harbour. Transects were designated A, B. C and D, respectively (Fig. 2-1). Several photographs were obtained at each site by raising and lowering the frame near the seabed over a 2-5 min period. A Benthos compass used as the camera trigger weight gave an indication of current direction at the time in each photograph. Macrophyte cover, sediment texture and the presence and absence of invertebrates >2 cm in length visible in photographs were recorded.

35 mm Ektachrome photographs using a Nikon FE camera were taken of the undisturbed surface layer of 131 0.1 m^2 Van Veen grab samples described in Chapter 1. Each grab was opened slowly to expose the sediment surface after allowing water to drain from the grab. Sediment was not sieved for determinations of macrofaunal biomass although some samples from stations in Bedford Basin were preserved with formalin for later identification of benthic fauna. Observations of tubes, burrows and tracks visible of the sediment surface were recorded as qualitative evidence of faunal activity.

Results

Bright sunlight and wave surges nearshore caused blurring of images in many underwater photographs. With the exception of brown humic water entering the upper end of Herring Cove, the camera and support frame were visible to 20 m depth. Nearshore sites off Tribune Head (A,B), Sandwich Point (C) and Fergusons Cove (D) (Fig. 2-1) where water depths were <10 m were characterized by exposed rock surfaces densely colonized by macrophytic brown algae (*Laminaria* spp. and *Fucus vesiculosus*). Other macroalgal species either observed in photographs or entangled in the frame on retrieval included *Desmarestia aculeata*, *Chondrus crispus* and *Porphyra linearis*. These are all common phaeophyceae and rhodophyta (brown and red) macroalgae found along exposed energetic rocky shores in eastern Canada (MacFarlane and Bell 1933, South 1976). Over the area surveyed the density of cover, qualitatively, was greatest at depths <10 m on rocky bottom near Tribune Head and least off Sandwich Point.

Attached macrophytes do not occur on exposed sandy sediments since holdfasts that anchor the plants require a firm substrate. The steeply sloped bottom off the western shore of the approaches to Halifax Harbour in the region of Sandwich Point and Tribune Head is composed of large boulders and exposed bedrock heavily colonized by macroalgae. Coarse gravel is interspersed between boulders which are covered with encrusting bryozoans and dense seaweeds. Coarse sand occurs at depths of 20 to 25 m off Tribune Head. Mollusc shell fragments, polychaete worm tubes and pieces of seaweed debris were present on the rippled sediment. There was no visible discoloration of surface sediment, expected if sulfides were accumulated, as discussed in Chapter 1. No anthropogenic debris was observed in the limited area covered by the photographs or collected as grab samples.

Attached seaweed biomass decreased with distance into Herring Cove. Exposed rock substrate was only present at the seaward end of the Cove. The centre part of the inlet is covered with mud and these areas are unsuitable for holdfast attachment. Also, the brackish nature of water, high humic content and effluent discharged into the head of Herring Cove may limit growth of these subtidal marine seaweeds. *Fucus vesiculosus* and *Ascophyllum nodosum* occur on protected shorelines at the seaward end of the Cove behind the breakwater. These intertidal seaweed species tolerate lower salinity than larger subtidal species.

Green sea urchins (*Strongylocentrotus droebachiensis*) and gasteropod snails (*Littorina*, *Lunatia*, *Buccinum*, and *Acmaea*) were visible in some photographs inside and near the entrance to Herring Cove. There was an accumulation of dead mussel shells (*Mytilus edulis*) in the area of the entry breakwater. Photographs along

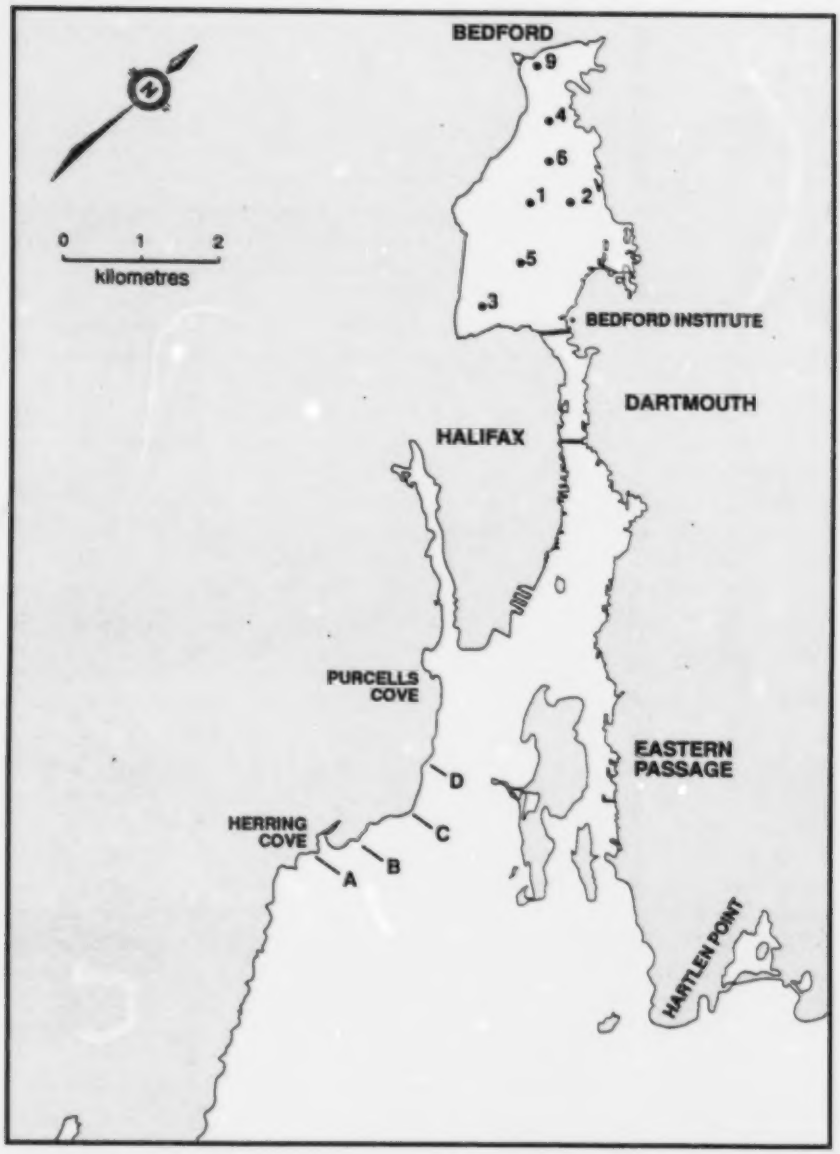

Figure 2-1. Location of seven stations sampled for benthic macrofauna in Bedford Basin between January and May 1970. Photographic surveys of the bottom to 30 m depth were carried out in October and November 1987 along transects A-D off the western shore of the approaches to Halifax Harbour.

transect (A) (Fig. 2-1) increasing in depth (7 to 25 m) from Tribune Head to the Bell Bouy showed the transition from macrophyte covered rocky areas (7 to 17 m) to gravel and sand (21 to 23 m) to sandy sediments with ripples (24 to 25 m) indicative of moderate bottom currents. Wave-generated bottom motion would reach this depth under storm conditions and tidal currents would produce sand ripples. Time series photographs are needed to establish the rates of formation and movement of these bottom features. Some macrofauna species listed above were visible on the exposed surface of the sand but numbers were small (1-5 individuals in a photograph) and they decreased with distance offshore. Only gasteropod snails (*Littorina*) and the mollusc (*Modiolus*) were identified in photographs at these deeper depths.

Transects extending offshore to depths of 30 m at Sandwich Point and Fergusons Cove indicated extensive beds of macrophytes over rocky bottom nearshore. The same species of macroalgae described at Tribune Head appeared in all areas attached to large rocks. Gravel and sand patches occurred between rocks at slightly deeper depths (15 to 20 m). Rocks were encrusted with bryozoans and mollusc shells were numerous. Few macroscopic invertebrates were observed but shading by macroalgae reduced the area of rocks and sediment visible in most photographs.

No obvious accumulations of mud occurred in any areas photographed to 25 m depth outside of Herring Cove. Suspended particulate matter was visible in surface water within 50 m of the Tribune Head outfall but no anthropogenic debris was observed floating or on the bottom. However, only a few hours were spent at the site. The intertidal area along the steep rocky shoreline is exposed to continuous wave action and debris was only observed stranded within Whatley Cove.

35 mm photographs of the contents of Van Veen grabs showed large differences in sediment texture that occur over short distances in Halifax inlet. Bottom topography is very irregular and muddy sediments accumulate in depressions. Many areas in the Harbour approaches have exposed rocks and bedrock outcroppings with no accumulation of sediments. Mud deposits in the central areas of Bedford Basin in water depths greater than 40 m appear to be homogeneous in texture. Samples from the western side along the Fairview and Rockingham shores contained interwoven tubes of the deep dwelling polychaete *Spiochaetopterus*. Tubes protruded up to 5 cm above the sediment surface and they penetrated to at least 20 cm. The majority of tubes were empty. The black sulfide rich sediments were oxidized at the surface with an orange layer 1-5 mm thick.

As in the approaches to Halifax Harbour, mid-channel areas of the central Harbour contained pockets of fine sediment between areas of exposed bedrock (shale and slate). When the grab collected pieces of rock at these sites, they were encrusted with coralline algae (*Lithothamnium*, *Corallina*) with a diverse attached fauna of sea urchins (*S. droebachiensis*), starfish (*Asterias*) and gastaropods (*Littorina*). Samples from Eastern Passage, inside of Drakes Passage, and the Narrows between the mainland and Lawlors Island, contained muddy sulfide-rich sediment. There were no tubes or burrow structures of benthic infauna visible on the sediment surface in these areas. Detrital debris (fragments of macroalgae and sea grass) was more abundant at these stations than elsewhere.

Sandy sediments graded rapidly to cobble and rock bottom with a high biomass of attached macroalgae, primarily *Laminaria*, *Agarum*, *Ulva* and *Desmarestia* outside of Drake Passage and off the shoreline leading to Hartlen Point. Exposed bedrock prevented sample collection at several stations off Hartlen Point. When the grab did obtain a sample it contained rocks, gravel and shell fragments. No seaweeds, attached or as debris, or benthic macrofauna were present in these samples.

One earlier study has provided data for comparison of benthic macroflora and macrofauna distribution in the approaches to Halifax Harbour (Elner and Hamet, 1984). They surveyed two sites off Fergusons Cove (5-12 m depth) where the hard bottom was comprised of boulders and cobbles on a sand-clay base prior to the dumping of 200 m^3 of dredged spoil removed from the entrance to Eastern Passage. Transects were examined by divers making visual observations of macroflora and fauna. Common attached macroalgae (*Agarum*, *Corallina*, *Desmarestia*, *Fucus*, *Laminaria*, and *Ulva*) were similar to the dominant species observed off

Sandwich Point and Tribune Head in the present study. The green sea urchin (*S. droebachiensis*) was the dominant epifaunal invertebrate but gasteropod species listed above were also present. Crustaceans such as crabs (*Cancer borealis, Cancer irroratus, Pagurus*) and lobster (*Homarus americanus*) observed by divers were not visible in our photographs. Low numbers (0-30 1000 m^{-2}) reported by Elner and Hamet explain the absence of individuals in photographs.

Benthic Macrofauna Biomass Distribution

An earlier report (Platt *et al.*, 1970) summarized observations of benthic macrofauna (animals >0.5 mm) in Bedford Basin from samples collected January 15 - May 16, 1970. A Van Veen grab (0.1 m^2) was used to take multiple samples (3-10) grabs at each of seven stations shown in Fig. 1. The grab collects sediment to a depth of 5-10 cm depending upon the relative percentages of mud and sand in deposits. Sediment was sieved through a 0.8 mm mesh to separate macrofauna >0.5 mm. The data have been tabulated in full here (Tables 1 and 2) to compare numbers and wet weight of different taxa.

The species diversity (numbers of different species/grab) is the lowest in samples from central Bedford Basin although up to ten replicate grabs were taken at station 6. The equivalent depth in St. Margarets Bay would contain from 20 to 30 different species. Only two species occurred at station 1 (70 m) in the centre of the Basin, four occurred at station 2 (60 m) and seven at station 5 (30 m). Station 9 near the Mill Cove sewage outfall contained 16 species while station 3 off Fairview Cove contained 7 species.

The most common macrobenthic species in Bedford Basin were polychaetes (segmented worms). The polychaete *Spiochaetopterus* has been collected in sandy sediments off the coast of Virginia (Miner, 1950). It has not been found in St. Margarets Bay, the Bay of Fundy or Browns Bank (Peer *et al.*, 1980). *Nereimyra* belongs to one of the least known families of Polychaeta. No species of this family have been found in samples from the Bay of Fundy or Browns Bank (Peer *et al.*, 1980, Wildish *et al.*, 1983) although two species of this genus were recorded from western Passage of Passamoquoddy Bay (Appy *et al.*, 1980). A species of this family was abundant in mud sediments in the deep central basin of St. Margarets Bay (Pocklington, 1984) and it was the second most abundant polychaete colonizing a dredge spoil dump site in deep water in the central area of Canso Strait (Pocklington, 1987).

K.L. Tay (personal communication) indicates that the polychaete community as described in this Halifax inlet study is quite different as compared with communities existing in other study areas in the Atlantic region. Polychaetes that were not found in most of the stations in the 1970 Halifax study existed (sometimes in great numbers) in other study areas (e.g. Strait of Canso and Bay of Chaleur), perhaps with the exception of the two genera, *Spiochaetopterus* and *Nereimyra*. *Spiochaetopterus* has a northern distribution and its occurence in Halifax Harbour extends its most southward distribution range (P. Pocklington, 1989). Although *Nereimyra* was found to be the second most abundant polychaete colonizing the northern part of the Canso dredge spoil dump site in the central area of Canso Strait in 1987, it was not found in a similar survey that was conducted in 1985, less than one year after the dumping of 90,000 m^3 of dredge spoil.

The burrowing sea anenome *Edwardsia* was another abundant genus. Although not found in St. Margarets Bay and only rarely in the Bay of Fundy, it was common in samples from Long Harbour in Placentia Bay, Newfoundland (Peer, 1972). It is normally considered a boreal species (Gosner, 1971). The holothurian *Molpadia oolitica* only occurred at station 4 at the entrance of Bedford Bay, but numbers were low (1 individual in 6 grabs), (Fig. 2-1). It has been found in St. Margarets Bay and St. Georges Bay where it burrowed deeply into well oxygenated sediments (Peer, 1972; Hargrave and Phillips, 1986). This species was also found in a dredge spoil site located in the Bay of Chaleur near Dalhousie, New Brunswick (Pocklington *et al.*, 1984; Pocklington, 1988).

The biomass of benthic macrofauna at the 7 stations sampled in Bedford Basin has a wide range of values (2-844 g wet weight. m^{-2}) with the highest levels at stations 9 and 4, off Mill Cove and at the entrance to Bedford Bay, respectively. The maximum biomass at station 9 was measured in a single grab and 67% of the total weight was present as two individuals of one mollusc species. This was the station with the

greatest species diversity. Five taxa occurring in this sample were not present at any other station. Stations at depths >43 m (1, 2, 5 and 6) in the central area of Bedford Basin had an average biomass of 36 g·m^{-2}. *Spiochaetopterus* was the only species to occur at all stations (Tables 2-1 and 2-2) but the range of biomass was large (<1 to 26 g.m^{-2}), (Tables 2-1 and 2-2).

Table 2-1. Mean numbers·m^{-2} (1 standard deviation in parentheses) for benthic macrofauna in sediment grab samples taken at seven stations in Bedford Basin shown in Fig. 1 between January 15 and May 16, 1970.

Taxa	Station Number						
	1	2	3	4	5	6	9
Depth (m)	70	55	21	21	55	43	<10
Sample Number	3	7	8	6	7	10	1
CNIDARIA							
Edwardisia	10 (17)	105 (82)	3	2 (4)	15	122 (55)	0
RHYNCHOCOELA							
Nemertea	0	1	16	70	70	11	0
MOLLUSCA							
Pelecypod	0	0	0	1	0	0	24
Gasterpod	0	0	0	4	0	0	60
ANNELDIA							
Plyllodoce sp.	0	0	23 (31)	18 (17)	2	0	13
Pholoe minuta	0	0	0	0	0	0	30
Gylcera capita	0	0	0	2	0	0	110
Nepthys	0	0	0	13 (18)	0	0	50
Maldanidae	0	0	2	2	0	0	1550
Prionospio	0	0	0	0	0	0	100
Laonice cirrata	0	0	0	13	0	0	0
Sabellidae	0	0	0	0	0	0	10
Lumbrineris	0	0	0	112	15	3	1270
Terebellides	0	0	0	0	0	0	280
Spiochaetopterus	53 (40)	393 (504)	4 (806)	38 (48)	150	450 (240)	20
Nereimyra punctata	0	1200 (776)	675 (393)	85 (108)	500	50 (30)	0
CRUSTACEA							
Amphipod	0	0	0	0	0	0	570
Isopod	0	0	0	0	0	0	80
Cumacea	0	0	10	75	9	0	90
ECHINODERMATA							
Asterias	0	0	0	3	0	0	40
Ophiuroid	0	0	0	5	0	0	0
Molpadia oolitica	0	0	0	2	0	0	0

Table 2-2. Mean biomass (g wet weight·m^{-2}) (1 standard deviation in parentheses) of benthic macrofauna taken in sediment grab samples at seven stations in Bedford Basin shown on Fig. 1 between January 15 and May 16, 1970.

Taxa	Station Number						
	1	2	3	4	5	6	9
Depth (m)	70	55	21	21	55	43	<10
Sample Number	3	7	8	6	7	10	1
CNIDARIA							
Edwardisia	5.7 (11.4)	24.5 (26)	>0.1	1.4 (4.3)	1.5 (3.7)	54.3 (29)	0
RHYNCHOCOELA							
Nemertea		0.7	0.1	0.6	2.2	4.3	0
MOLLUSCA							
Pelecypod	0	0	0	40.0	0	0	566.0
Gasterpod	0	0	0	>0.1	0	0	15.0
ANNELDIA							
Plyllodoce sp.	0	0	0.01 (0.14)	0.04 (0.04)	<0.01	0	0.5
Pholoe minuta	0	0	0	0	0	0	0.2
Gylcera capita	0	0	0	0.4	0	0	6.0
Nepthys	0	0	0	0.09 (1.3)	0	0	22.7
Maldanidae	0	0	<0.01	<0.01	0	0	131.9
Prionospio	0	0	0	0	0	0	0.1
Laonice cirrata	0	0	0	3.4	0	0	0
Sabellidae	0	0	0	0	0	0	0.4
Lumbrineris	0	0	0	7.1 (4.3)	1.0 (2.3)	0.4	42.7
Terebellides	0	0	0	0	0	0	1.1
Spiochaetopterus	3.5 (0.4)	22.9 (25.0)	<0.01	2.6 (4.6)	3.2 (22)	25.9 (12)	1.9
Nereimyra punctata	0	2.5 (1.0)	1.2 (0.6)	0.05 (0.07)	0.40 (0.09)	0.02	0
CRUSTACEA							
Amphipod	0	0	0	0	0	0	6.8
Isopod	0	0	0	0	0	0	0.3
Cumacea	0	0	<0.01	0.07	<0.01	0	0.5
ECHINODERMATA							
Asterias	0	0	0	7.4	0	0	47.7
Ophiuroid	0	0	0	2.0	0	0	0
Molpadia oolitica	0	0	0	64	0	0	0
TOTAL BIOMASS (g·m^{-2})	7 (12)	71 (52)	2 (1)	152 (110)	8 (31)	59	844

The range of biomass of macrofauna observed value at station 9 is similar to values reported previously for 30 m depth in St. Georges Bay (69 to 143 $g.m^{-2}$) (Hargrave and Phillips, 1986) and the central area (50-70 m) of St. Margarets Bay (27 to 42 $g.m^{-2}$) (Hargrave and Peer, 1973). Samples from a shallower depth (10 m) in sandy sediments contained 53 (sd = 14) $g.m^{-2}$. An overall mean for approximately 40 stations throughout St. Margarets Bay was 45 g. m^{-2} with a range of values from 26 to 300 $g.m^{-2}$. A comparable value for all stations in Bedford Basin excluding station 9 is 50 $g \cdot m^{-2}$ (range 2 to 152).

Areas of the Bay of Fundy have a much greater range of benthic macrofauna biomass (up to 3 kg wet weight.m^{-2}). This is thought to reflect the importance of vertical tidal transport of particulate matter used as food by suspension feeding bivalves (Peer *et al.*, 1980; Wildish and Kristmanson, 1979). Corresponding values in the southern Gulf of St. Lawrence (Magdalen Shallows) (50 m depth) vary from 34 to 650 $g \cdot m^{-2}$ with a mean value of 250 $g \cdot m^{-2}$ (D. Peer, unpublished data). Fine sandy sediments that are well-oxygenated generally support a higher biomass of benthic macrofauna because of optimum conditions of food and dissolved oxygen supply (Parsons *et al.*, 1984). Future studies within Halifax inlet could quantify these relationships.

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CHAPTER 3

DISSOLVED AND PARTICULATE TRACE METAL DISTRIBUTIONS IN HALIFAX HARBOUR

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ABSTRACT

This report presents data obtained on dissolved and particulate trace metals in the waters of Halifax Harbour. These data were acquired on January 18th and January 30th, 1989, to complement a much larger survey of trace metal concentrations in sediments.

The levels of dissolved trace metals in the waters of Halifax Harbour are comparable with those in other nearshore waters of the region and are generally about a factor of two to five higher than levels in Scotian Shelf surface waters. High concentrations were seen for zinc in Dartmouth Cove and manganese in the deepest waters of Bedford Basin. The high manganese concentrations result from the release of dissolved manganese from the underlying sediments. Particulate metal concentrations are also generally comparable to those found in the few reports of metal concentrations in nearshore areas. High concentrations of particulate cadmium and zinc were found in Tufts Cove and high particulate manganese concentrations occurred throughout Bedford Basin.

Only the most qualitative discussion of this data is possible because it is based on a single "snap-shot" picture of a dynamic situation. Considerable attention to understanding the variability in the dissolved and particulate metal distributions is required before a more detailed discussion of the metal distributions or the interactions with the sediments can be developed.

INTRODUCTION

A recently completed survey of sediment quality in Halifax Harbour (Buckley *et al.*, 1989) included extensive measurements of trace metal concentrations in the harbour sediments. Very high levels of zinc, copper, lead and mercury were found at several locations in the harbour. The anomalies were generally adjacent to sewage discharges but there were some interesting differences in the extent of metal contamination at the various discharges and the location of anomalies for different metals. In this paper we report the concentrations of dissolved and particulate metals in the waters of Halifax Harbour. The station locations were chosen with a knowledge of the sediment results and the intention of sampling the water over the sediments with highest metal concentrations. The samples were also collected on a falling tide so they should reflect the maximum water column concentrations at these anomalies rather than an average distribution.

METHODS

The collection of water samples for metal determination was conducted in two stages. In the first stage, water samples were collected on January 18th, 1989, for the measurement of salinity, suspended particulate matter (SPM), nutrients, and the metals copper (Cu), zinc (Zn), lead (Pb), manganese (Mn), cadmium (Cd) and nickel (Ni). Thirteen samples were collected at seven locations in the Harbour (Figure 3-1)

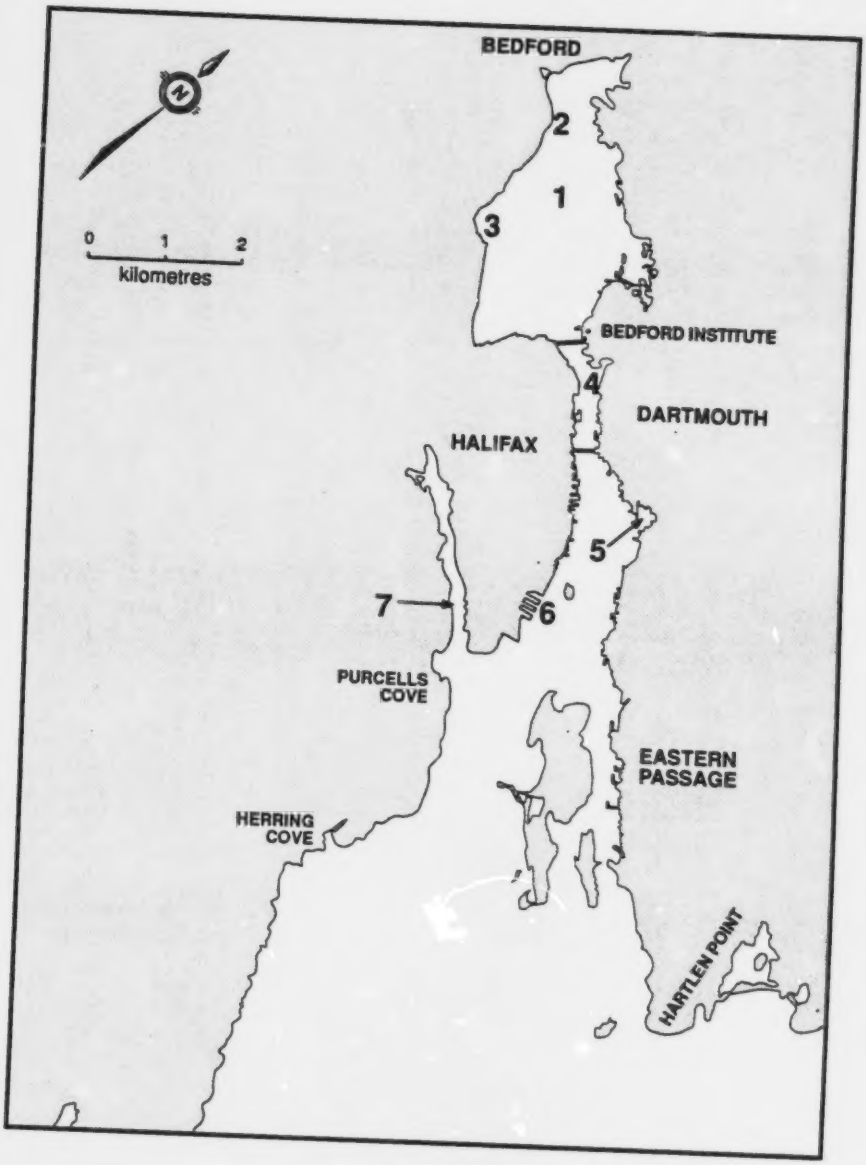

Figure 3-1 Location of stations for collection of water samples for metal determination.

between 0915 and 1150 hours (AST) on a falling tide (low water was at 1155 hours). Separate unfiltered water samples were retained for nutrient analysis and salinity determination. The water samples intended for trace metal analyses were filtered through acid cleaned and tared 0.4 um pore-size Nuclepore filters and acidified with high purity acid (5 mL Seastar hydrochloric acid per 2 L water sample) in the laboratory by 1200 hours on Jan 19th.

Analysis of the filtrates was conducted using the methods of Danielsson *et al.* (1982), for Zn, Pb, Cd, Ni and Cu, and Bewers *et al.* (1976) for Mn. The filters were washed to remove residual salt, dried, reweighed and stored for later trace metal analysis. The suspended matter samples were decomposed in LORRAN teflon-PTFE digestion bombs for 45 seconds with 1 mL of aqua regia and 1 mL of HF (Ultrex grade) in a microwave oven (Rantala and Loring, 1989). The fluorides were dissolved using 0.5 g of boric acid crystals and the solutions were made up gravimetrically to the equivalent of 10 mL in polypropylene bottles. The metals were determined using either flame (Fe, Mn, Zn) or graphite furnace (Al, Cd, Cu, Pb) atomic absorption spectrophotometric methods (Rantala and Loring, 1977, 1985).

In the second sampling stage, which took place between 0915 and 1230 hours (AST) on January 30th during a rising tide (low water was at 0815 hours), samples were collected at the same locations for the measurement of 'reactive' mercury (Hg). These samples were acidified (3 mL nitric acid per 500 mL water sample) and analyzed within 48 hours of collection using the technique of Dalziel and Yeats (1985).

Table 3-1. Salinity, suspended particulate matter and dissolved Cu, Zn, Mn, Pb, Cd, Ni and Hg concentrations in Halifax Harbour samples

Location Station (Depth)	Sample Depth (m)	Salinity (ppt)	SPM	Mn	Ni	Cu	Zn	Cd	Pb	Hg
			mg/L	µg/L						ng/L
Station 1 Compass Buoy (71 m)	1	29.606	0.57	3.82	0.65	0.62	4.13	0.053	0.049	0.35
	5	30.010	0.68	2.93	0.48	0.40	3.75	0.029	0.023	0.49
	15	30.246	0.52	2.25	0.53	0.47	3.50	0.030	0.021	0.66
	25	30.496	0.36	2.74	0.51	0.43	6.45	0.030	0.016	0.27
	50	31.338	0.24	18.90	0.37	0.32	4.46	0.017	0.010	0.35
	60	31.404	0.54	14.00	0.35	0.40	3.51	0.014	0.018	<0.10
Station 2 Off Clearwater (20 m)	12	30.187	0.51	2.87	0.54	0.36	5.19	0.036	0.020	1.08
Station 3 Birch Cove (28 m)	20	30.431	0.39	1.30	0.47	0.40	7.33	0.038	0.024	0.43
Station 4 Tufts Cove (15 m)	8	30.359	0.48	2.49	0.66	0.45	6.57	0.037	0.036	0.11
Station 5 Dartmouth Cove (11 m)	5	29.744	1.32	6.49	0.59	0.81	11.3	0.048	0.055	0.72 0.49*
Station 6 Georges Island (20 m)	3	30.623	0.66	2.55	0.48	0.49	4.38	0.029	0.030	0.52
	14	30.851	0.73	2.17	0.42	0.35	2.31	0.030	0.055	0.30
Station 7 Northwest Arm (14 m)	8	30.492	0.89	2.90	0.45	0.46	2.75	0.035	0.051	1.08

* denotes replicated value

DISSOLVED TRACE METALS

The concentrations of dissolved metals in the water samples are given in Table 3-1. Dartmouth Cove contains the highest levels of Zn, Cu, and Pb and relatively high levels of Ni, Cd and Mn, all of which can be attributed to local run-off and waste discharges including those from the Dartmouth Shipyards. The Dartmouth Cove sample also had the lowest salinity and the highest suspended particulate matter concentrations. Another notable feature of the results is the high levels of manganese in the deeper part of the Bedford Basin. These high Mn concentrations can be attributed to the geochemical process of reduction of Mn^{4+} to Mn^{2+} in anoxic bottom sediments and the subsequent migration of reduced manganese into the overlying waters. The appearance of excess manganese in bottom waters overlying anoxic sediment as a result of this process is a common feature of relatively slow-moving coastal bottom waters (Yeats *et al.*, 1979).

Table 3-2 provides a comparison of the average levels of dissolved metals from the six shallow stations (2-7) surveyed in Halifax Harbour with data obtained from previous measurements in the Harbour and at other nearshore and coastal areas. Port Medway is located at the mouth of the Medway River about 100 km southwest of Halifax. The samples of coastal water on the Scotian Shelf were collected on BIO cruise 85-017 during June 1985. This comparison shows that the average levels of dissolved metals in Halifax Harbour are generally about twice those found at Fergusons Cove in the outer Harbour and at Port Medway. Cu, Ni and Cd levels in Halifax Harbour are one and a half to three times levels on the Scotian Shelf and Pb concentrations are within the range found on the Shelf. Mn and Zn concentrations in the Harbour are considerably higher than those on the Shelf because active removal processes decrease the levels. As a result, the Halifax Harbour concentrations should only be compared

Table 3-2. Comparison of dissolved metal concentrations in Halifax Harbour with concentrations in other coastal areas.

Location		Mn	Ni	Cu	Zn	Cd	Pb	Hg
		ug/L						ng/L
Halifax Harbour (Mean: Stations 2-7 of this survey)		3.04	0.52	0.47	5.91	0.037	0.040	0.60
Fergusons Cove 1988		1.00	0.30	0.28	1.02	0.023	-	-
CASS-2*	1988	1.99	0.30	0.67	1.97	0.019	0.019	-
Sandwich Point	November 1987	1.36	0.49	0.49	4.97	0.026	-	-
	August 1987	0.81	0.27	0.25	0.67	0.030	-	-
	May 1987	0.32	0.30	0.28	2.09	0.022	-	-
Off Volvo Wharf	1982	-	0.76	0.88	2.85	0.038	-	-
Herring Cove	1985	-	-	-	-	-	-	1.20
	1986	-	-	-	-	-	-	1.25
Port Medway	1988	1.10	0.35	0.32	2.90	0.056	-	-
Scotian Shelf Surface Water Range (Cruise 85-017)		0.2-1.8	0.21-0.30	0.18-0.29	0.06-1.20	0.015-0.029	0.01-0.08	0.24-0.93

*CASS-2 is a National Research Council of Canada water sample collected from Fergusons Cove that is being prepared for issue as a certified reference material under the Marine Analytical Chemistry Standards Progrzam

to inner Scotian Shelf levels at comparable salinities. In such a comparison, Halifax Harbour Mn and Zn concentrations respectively are approximately twice and five times those on the Shelf.

Comparison of levels of dissolved metals from one location to another should only be made with an appreciation of the variability in the results. This variability would include analytical variability in the laboratory determinations and environmental variability, both temporal and spatial. Although there can be no indication of temporal variability in the harbour data set, we do have some indication of the temporal variability in the region (Fergusons Cove, Sandwich Point) immediately outside the present sampling area. A comparison, using a t test, of the outer harbour with those for the inner harbour and Bedford Basin (Table 3-3) will give some idea of the significances of the differences in concentration between the areas. The t tests show that the concentrations of Zn, Cd, Pb, Ni and Mn in the outer harbour are different from those in the inner harbour ($p<0.025$). Only lead shows differences within the harbour as indicated by a significant difference between the concentrations in Bedford Basin and those on stations 4-7.

TRACE METALS IN SUSPENDED MATTER

Results for the total metal analyses of the suspended particulate matter samples are listed in Table 3-4 together with results of some SPM analyses from other coastal areas (Table 3-5). A comparison of the Halifax Harbour results with those reported for the outer harbour (Fergusons Cove), La Have estuary and St. Lawrence estuary show that the levels of Cd and Pb in Halifax Harbour are similar to those in the other regions with the exception of anomalously high levels of Cd in Tufts Cove. Copper and Zn levels are generally higher than those reported for the other regions but the only striking anomaly is the high level of Zn in Tufts Cove. A comparison of the Bedford Basin results with those of an earlier report of particulate metal concentrations in a Bedford Basin sample (Yeats and Dalziel, 1987) shows very little difference for any of the metals.

The particulate Mn, Fe and Al results at the station in the center of Bedford Basin are interesting. Very highly elevated concentrations of particulate Mn are seen on the deepest samples in the basin with concentrations decreasing at shallower depths. These observations are consistent with the observed distribution of dissolved Mn and the mechanism for release of

Table 3-3. Average dissolved metal concentrations in different parts of Halifax Harbour

Location		Mn	Ni	Cu	Zn	Cd	Pb	Hg
		ug/L						ng/L
Outer Harbour[1]	$\bar{x}$	1.10	0.33	0.38	1.88	0.024	-	-
	s	0.62	0.08	0.17	1.55	0.004	-	-
	n	5	6	6	6	6	-	-
Stations 1-7[2]	$\bar{x}$	2.96	0.53	0.48	5.24	0.036	0.035	0.54
	s	1.32	0.08	0.13	2.58	0.008	0.015	0.30
	n	11	11	11	11	11	11	12
Stations 1-3[2]	$\bar{x}$	2.65	0.53	0.45	5.06	0.036	0.026	0.55
	s	0.84	0.06	0.09	1.56	0.009	0.012	0.29
	n	6	6	6	6	6	6	6
Stations 4-7	$\bar{x}$	3.32	0.52	0.51	5.46	0.036	0.045	0.54
	s	1.79	0.34	0.17	3.66	0.008	0.012	0.34
	n	5	5	5	5	5	5	6

1 Fergusons Cove/Sandwich Point samples from Table 3-2

2 The two deepest samples from station 1 have been excluded in these comparisons

Table 3-4. Particulate metal concentrations in Halifax Harbour

Station/Depth #/m	Mn	Cu	Zn	Cd	Pb	Fe	Al
	ug/g					%	
1/1	7130	198	444	1.2	359	5.30	4.20
1/5	8150	151	370	1.2	209	4.30	3.46
1/15	10100	168	474	1.1	229	3.95	2.63
1/25	13400	165	617	1.4	282	4.67	2.73
1/50	23800	80	400	1.8	205	13.90	1.13
1/60	12500	46	340	1.0	72	10.40	0.44
2/12	10500	165	741	1.2	198	4.43	2.52
3/20	15500	165	667	1.9	302	4.49	2.44
4/8	7060	266	1570	8.7	298	4.04	2.55
5/5	1520	367	606	2.8	239	3.73	2.55
6/3	2130	176	312	1.3	172	3.32	4.51
6/14	1640	147	311	1.4	196	4.32	4.51
7/8	894	173	247	0.8	214	3.18	2.29

Table 3-5. Comparison of particulate metal levels in Halifax Harbour with concentrations in other coastal areas

Location	Mn	Cu	Zn	Cd	Pb	Fe	Al
	ug/g					%	
Halifax Harbour (Mean: Stations 2-7)	5610	208	636	2.6	231	3.93	3.05
Fergusons Cove[1]	1620	55	250	1.8	152	2.06	3.26
St. Lawrence estuary[2]	834	43	241	3.5	67	4.35	6.81
La Have estuary[3]	698	89	199	-	200	5.26	6.94
Bedford Basin[1]	8080	135	525	1.8	288	2.47	2.56

1 Dalziel and Yeats, 1987
2 unpublished results - mean for high salinity samples from cruise 76-006
3 Cranston *et al.*, 1975 - mean for stations 8, 9 and 10

dissolved Mn from anoxic sediments and subsequent reprecipitation within the water column (Yeats *et al.*, 1979). It would appear from the particulate Mn distributions observed in the present study that particles with high Mn content are advected throughout the basin and into the rest of the harbour. These particles would appear to be observed as far seaward as the surface sample at Georges Island. High concentrations of particulate Fe are also seen in the deepest samples from Bedford Basin. Since Fe should also be reduced and mobilized in anoxic sediments, the mechanism for enrichment of Fe on these particles is likely to be the same as that for Mn.

CONCLUSIONS

The levels of dissolved and particulate metals in the waters of Halifax Harbour are somewhat elevated over the levels seen on the Scotian Shelf or at other coastal sites in Nova Scotia. Some of the metals are not elevated to any measurable extent while for the others the average concentrations are no more than three to five times the levels in the other areas. The most elevated individual samples from this survey are six times those in the outer harbour. The exception to these observations is the high concentrations of dissolved and particulate manganese and particulate iron in the two deepest samples from Bedford Basin that result from natural redox reactions.

There is a general increase from the outer harbour to the inner harbour for dissolved metals, particulate metals and metals in the sediments. There are also some similarities in the locations of the anomalies for the different phases. The most obvious coincidences are the Basin bottom water for dissolved and particulate manganese and Tufts Cove for particulate and sedimentary zinc. In general the highest concentrations of dissolved metals were seen in Dartmouth Cove, while for particulate metals and metals in sediments (Buckley *et al.*, 1989) the biggest anomalies were often in Tufts Cove. The Northwest Arm site is noteworthy since, despite elevated organic matter in the sediments, the dissolved, particulate and sediment metal concentrations are relatively low.

It is difficult to draw many conclusions from the dissolved and particulate metal results because we know there must be a lot of variability in the distributions in time and space that we have not characterized. The sediments will tend to integrate the signals for metal inputs to the sediments over time periods that may be of interest. Water column concentrations are likely to be subject to high frequency fluctuations as a result of factors such as tidal and wind mixing, and changes in freshwater input from rivers, rainfall and outfalls. Consequently, it is difficult to make definitive comparisons between levels of metals in water and sediments and the locations and magnitudes of anomalies. In order to draw any stronger conclusions than the very general comparisons that we have been able to make in this paper, it will be necessary to undertake an investigation of the variability of the metal distributions in the waters of Halifax Harbour.

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CHAPTER 4

PHYSICAL OCEANOGRAPHY AND MODELLING IN HALIFAX HARBOUR: A REVIEW

by
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INTRODUCTION

Although a great amount of research has been done in Halifax Harbour (Hargrave and Lawrence, this report), most of the work was only very indirectly related to pollution. However, since the 1970's, a series of applied studies has been carried out on the impact of sewage on the Halifax Harbour environment and on possible abatement methods (summarized in ASA Consulting Ltd., 1985). Over the same period, physical and biological data were collected largely by the federal Department of Fisheries and Oceans. Analyses were carried out (ASA Consulting Ltd., 1986) to determine and quantify the processes at work and to develop a set of predictive models that were used to explore a variety of scenarios (CBCL Ltd., 1987). This paper is a review of the physical processes and the modelling to help in the interpretation of the other studies described in this report. It will also provide background for an upcoming physical oceanographic/modelling study funded by the Atlantic Canada Opportunities Agency (ACOA) and the Nova Scotia Department of the Environment (NSDOE), with support from the Bedford Institute of Oceanography (BIO).

PROCESSES

One can consider four ways in which the harmful effects of sewage disposal into an inlet can be diminished:

(1) removal of components by <u>treatment</u> before discharge,

(2) natural <u>decay</u>, and burial within sediments.

and the physical oceanographic processes of:

(3) dilution by <u>mixing</u>, and

(4) transport away from the region by <u>advection</u>.

Now follows a review of mixing and advection.

<u>Mixing</u>

This can cause direct dilution of all components of the discharged sewage, as well as bringing in oxygen to replace that used up by chemical and biological reactions. There are a number of processes that can cause mixing:

- Friction of the currents against the bottom can cause vertical and horizontal shears.

- The presence of small scale topographic features can disturb the tidal or wind driven currents, resulting in eddies. The outer Halifax Harbour has several such features.

- Shear due to fresh water inflow: in Halifax Harbour both sewage and normal fresh water must be considered as they have comparable volumes. The effect can be seen in The Narrows (McGonigal *et al.*, 1974).

- Intrusions of offshore water over the sill and into Bedford Basin. These happen

irregularly, and the mechanisms are not fully understood. The evidence is seen in the time series plots of salinity, oxygen and silicate vs. depth (Krauel, 1969). A detailed analysis (ASA Consulting Ltd., 1986, Appendix B) yielded correlations between harbour bottom water density and longshore Scotian Shelf winds that were significant at the 95% level for periods longer than 5 days. However, there was no correlation between the occurrence or volume of intrusions and the wind. Prediction of intrusive events will require a much greater knowledge of water properties and motions on the shelf.

- The local wind which creates shear between surface and underlying waters. Its effect becomes relatively important where currents due to the other major driving force, the tides, are weak, i.e., near the deeper, wider oceanic entrance and near the head of the inlet.

- Mixing at the outfalls. The ends of outfall pipes can be fitted with diffusers which create many high speed jets. The contrast in velocities creates much turbulence which entrains large volumes of the surrounding cleaner water. Preliminary design (CBCL Ltd., 1987) indicates that initial dilutions of 50:1 can be achieved in 20 m of water depth for sites in the harbour.

A complete quantification of all of these mixing processes was carried out in support of the modelling of Halifax inlet (ASA Consulting Ltd., 1986, Phase 2, Appendix B). The strengths of these various mixing processes can be seen in the values of the equivalent eddy diffusivities (Table 4-1). Note that the relative importance will vary over the inlet as many processes have spatial dependence and will vary with time as departures from the average hourly wind strength (4.8 m/s) occur. As well, there are uncertainties due to the semiempirical nature of many of the formulations used. Nevertheless, the dominance of tidal mixing is apparent.

Advection

This can serve to transport pollutants away from the region and bring in clean water, but can also recirculate contaminated water, thereby

Table 4-1. Summary of mixing mechanisms at work in Halifax inlet as illustrated by eddy diffusivities (from ASA Consulting Ltd.,1986).

Energy Sources	Tides	Wind
SUBGRID PROCESSES - vertical diffusion - horizontal diffusion due to vertical shear dispersion	K_V (0 to 0.0004 m^2/s)[a] K_H (0 to 1 m^2/s)[b]	K_V (0.001 m^2/s)[c] K_H (5 m^2/s)[c]
INTERMEDIATE PROCESSES - lateral diffusion due to horizontal shear dispersion	K_H (0 to 50 m^2/s)[b]	K_H (1 to 10 m^2/s)[d]
LARGE SCALE PROCESSES - time dependent circulation - mean circulation	K_H (0 to 500 m^2/s)[b] K_H (0 to 25 m^2/s)[e]	K_H (3 to 50 m^2/s)[d]

↑ explicitly considered in the model

a dependent on local tidal current (amplitude)^3
b dependent on local tidal current (amplitude)^2
c independent of location
d dependent on the local dimensions of the harbour
e dependent on the local velocity and length scale of residual circulation

compounding the problem. The process can conveniently be divided into tidal and nontidal:

- Tidal: the multiyear tide height record from the reference station at Halifax is dominated by the semidiurnal M_2, with an amplitude of 63.3 cm (note M_2 accounts for nearly 60% of the tidal elevation). The corresponding M_2 horizontal velocity from several one-year records in The Narrows (Fig. 4-1) has an amplitude of 23 cm/s (McGonigal *et al*, 1974). A recent hydrodynamic model (ASA Consulting Ltd., 1986) driven by the M_2 tide height reproduces The Narrows current over an extreme range of bottom friction values (Manning numbers in the quadratic Chezy formulation of $N = 0.01$ to 0.08, corresponding to 'glassy smooth' to 'weedy crooked' bottom types). Although the tidal currents are dominant in amplitude, their excursion is relatively small over most of the harbour but reaching 3.3 km in The Narrows. Their main importance in the sewage problem is in the mixing they promote.

- Non-tidal currents can arise from a variety of sources:
  - Wind: the mean wind stress over the shelf in most seasons ($\tau \sim 0.03$ Pa, Thompson and Hazen, 1983) could drive an upper 10 m thick layer at a mean velocity of $u = \tau/\rho hf \approx 0.03$ m/s. In winter, values would be up to $\times 2$. Calculations based on Sable Island wind spectra (Petrie and Smith, 1977) give similar results. Velocities might be reduced in the confines of the Halifax inlet, but would still be significant. Salinity sections (Jordan, 1972) show that moderate winds push the surface fresh water to one side or the other of the Harbour, depending on their direction.
  - Tidal rectification: when a periodic force drives currents over and around obstructions, the flow often takes a slightly different path between inflow and outflow resulting in a net mean flow. Since the tidal flow in most of the inlet is weak (in the range of 10's of cm/s), the rectified current would be expected to be in the range of a few cm/s (confirmed by modelling, ASA Consulting Ltd., 1986). This might have a slight effect on the placement of outfalls and their dilution efficiency.
  - Seiches: these are natural resonances of semi enclosed bodies of water. The natural period of the Harbour and Basin combined was calculated as 2.1 hours and currents with this period were seen in The Narrows data (McGonigal *et al.*, 1974). Although the amplitude can be comparable to that of the tides (6 cm/s), the excursion distance is relatively short (0.14 km).
  - Internal currents: although the non tidal net flow through any section across the Harbour is near zero (just sufficient to balance the fresh water inflow), there can be internal circulations both lateral and vertical. In The Narrows, it was observed (McGonigal *et al.*, 1974) that the tidal residual currents showed outflow in the surface layer and inflow in the lower layer. This was attributed mainly to the local wind and not to daily averaged river inflow. No details were given. A more formal analysis (Heath, 1973a) concluded that the daily mean currents in both The Narrows and the entrance to St. Margaret's Bay were in phase horizontally in the surface layer, out of phase between surface and bottom layers, and that this phenomenon was correlated with atmospheric pressure or winds.

The picture might change when one considers longer term means. Then the wind influence becomes less important as its mean decreases, and forcing by river input and the Scotian Shelf coastal current can become more important. Huntsman (1924) on the basis of a few drift bottles concluded that in the surface layer there was inflow through the Harbour and into Bedford Basin. The 20-25 day means from The Narrows current meter data (McGonigal *et al.*, 1974) have been further analyzed for internal currents in Table 4-2. The conclusions are that there is a seaward flow at 3 m (1.2 cm/s), and landward flows at 8 m (2.4 cm/s) and 17 m (3.7 cm/s). At 3 and 8 m there was no significant difference in the flows between left and right sides, but at 17 m the inflow was stronger on the right side by 6.2 cm/s. Lewis and Platt (1982)

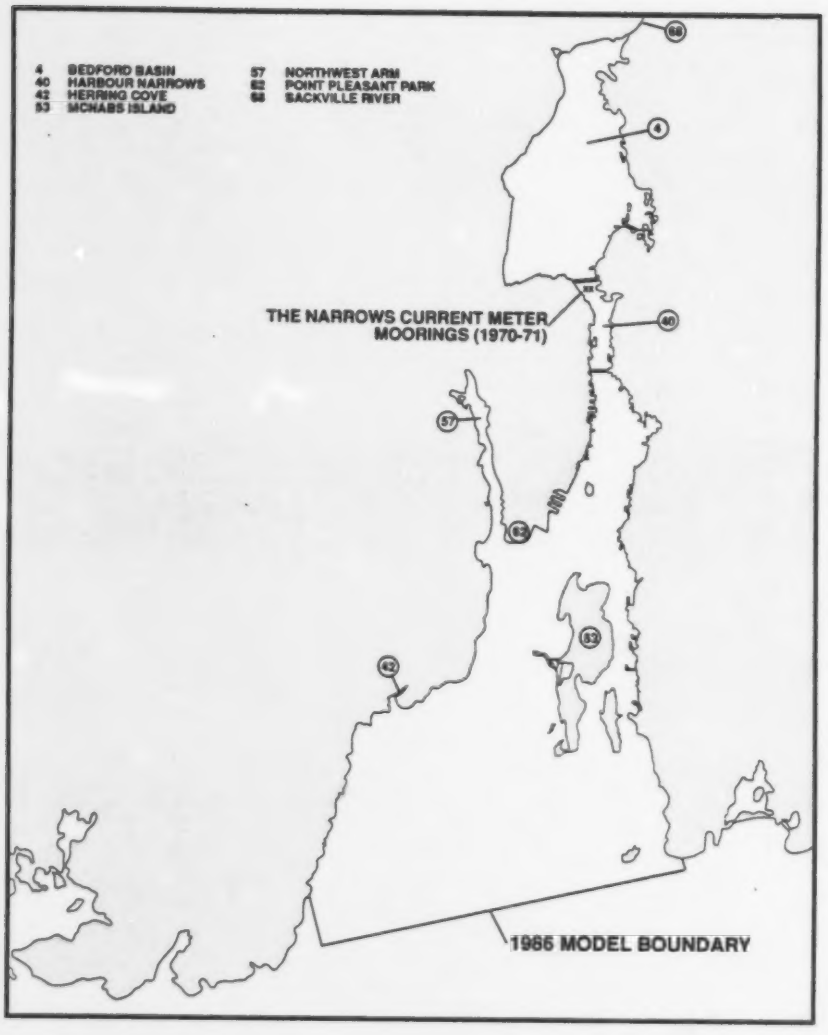

Figure 4-1. Location of 1970-71 current-meter moorings in The Narrows and 1986 model boundary.

also used this current meter data. Starting with the raw data, the tides were removed by harmonic analysis, then a low pass filter was applied. Examination of 40-60 day blocks in summer and winter led to the conclusion that the flow was seaward at 3 m and landward at 17 m.

The annual fresh water flow rate into Bedford Basin is about 7 m^3/s (see CBCL Ltd., 1987, Appendix D, sum of regions 3a-c, 4a-c, 5, 6) of which the Sackville River contributes 80%. If this is postulated to drive an internal circulation, then using an effective upper layer depth of 10 m in The Narrows with a salinity reduced from 30 to 29 ppt and a cross section area of 3000 m^2, one estimates a velocity of 7 cm/s, which is of the same order of magnitude as that observed. Thus this mechanism seems feasible even if not proven at present. It should be noted that the total fresh water inflow to the entire harbour is 16 m^3/s and of this the amount due to sewage is 2 m^3/s.

Given the oceanographic measurements, flushing times for the upper layers (top 20 m) of Bedford Basin have been calculated (ASA Consulting Ltd., 1986, Appendix B). The wide range of values reflects the variety of methods used; all based on very simple approximations. Using the formulation volume ÷ (cross section area × velocity), with currents taken from integration of the power spectra, estimates were 53 days in winter and 83 in summer, a significant increase over the 5 days obtained earlier by Lewis and Platt (1982). Using tidal currents with this formulation resulted in similar values. Using the same method but with monthly mean measured currents gave 23 days. Using a tidal prism method gave 7 or 4.3 days depending on whether recycling (60%) of the water was assumed or not. A salt balance method gave 7 days. As far as estimating the importance of internal circulation, the Hansen Rattray estuary classification method indicated that internal flow accounted for half the transport in The Narrows and Harbour, and nearly all in Bedford Basin, whereas flow estimates based on volumetric measurements predicted only a 10% contribution.

In the central harbour, the internal circulation has been postulated to be horizontal and counterclockwise, although there are few direct measurements. Huntsman (1924) deduced this from temperature-salinity stations; nine occupied once in winter and two occupied three times in summer. He attributed the circulation pattern to the Scotian Current. A recent sewage disposal study (CBCL Ltd., 1977) repeats this picture with the Scotian Current

Table 4-2. Halifax Narrows, axial currents 1970-71[1].

Depth	Station Means ± std. dev. + = inward (300° T)		Lateral Mean 0.5 (east + west)	Lateral Difference (east − west)
	Station 65[2] Dartmouth Side (east)	Station 66[2] Halifax Side (west)		
3 m	-1.0 ± 2.5	-1.4 ± 3.0	-1.2 ± 2.5	0.5 ± 2.6
8 m	2.6 ± 2.3	2.1 ± 3.1	2.4 ± 2.6	0.6 ± 1.9
17 m	6.7 ± 2.1	0.5 ± 3.0	3.7 ± 2.2	6.2 ± 3.0

1 velocities in cm/s; std. dev. based on 7 blocks of 20-25 days each

2 see Fig. 4-1 for station locations

coming down the coast at 8 km/day (9 cm/s) and sweeping into Halifax Inlet on the east and out on the west. Velocities of 5 cm/s were used in various outfall scenarios on the west side. Support for this picture was found in the most recent analysis (ASA Consulting Ltd., 1986, Appendix B) of earlier extensive year-long, temperature-salinity data (Jordan 1972). An extensive set of current meter measurements in St. Margarets Bay, a larger nearby inlet, showed such a counter clockwise circulation (Heath, 1973b) forming an extension of the circulation on the Scotian Shelf outside the Bay.

The recent modelling of the currents in the Harbour (ASA Consulting Ltd., 1986), although driven only by a single tidal constituent (M_2), did show that eddies could be generated by rectification. The eddies, although quite weak, were in the Point Pleasant Park-Herring Cove area of the outer harbour, which is a possible major outfall site. They were not all counterclockwise. The predicted strength and positions of these eddies were quite sensitive to the uncertainties in the choice of diffusivities and bottom roughness. Huntsman (1924) had postulated a single large weak counterclockwise eddy south of the entrance to the Harbour, but on the basis of only 5 surface drift bottle returns. The upcoming field program referred to in the introduction will use moored current meters to delineate the circulation patterns in the outer harbour, in particular to map the Scotian Current intrusion. The data will be used to upgrade the hydrodynamic model to include this forcing, and to fine tune the diffusivity and bottom roughness parameters.

MODELLING

An extensive modelling effort formed the heart of the most recent pollution study of Halifax Inlet. By the end of the 3rd phase of the study, a variety of models had been used:

(a) Freshwater budget and pollution loading: this combined box model (ASA Consulting Ltd., 1986, Appendix A) is unique in that it has been designed to account for the complete fresh water balance in the metropolitan area, by distributing net meteorological input and imported water over the entire area, and by assigning total pollution loads based on population and land use within each drainage area. The loading model can generate loads on an annual average, seasonal average, and storm event basis. The loads enter the Harbour through individual rivers and streams, general groundwater, specific sewer outfalls and storm overflows. Calibrations were done against the Sackville River flow and against the volumes and loadings from the two existing sewage treatment plants and 8 selected outfalls.

(b) Box model: this simple form of modelling was developed for Bedford Basin (ASA Consulting Ltd., 1986, Appendix C) for two major purposes - to quantify the fluxes across the false bottom that was to be used with the main hydrodynamic model, and to estimate the eutrophication potential for the deep Basin waters. Three layers were used for the Basin, driven by the Sackville River inflow at the surface and 3 layer exchanges through The Narrows. Calibrations were done using the earlier DFO salinity data (Krauel, 1969; Jordan, 1972). The results showed that tidal and wind-induced mixing through exchange at The Narrows are far more significant to dispersion in the upper Basin than is the mixing due to the occasional shelf water intrusions. The model, which did not consider the effect of sediments, predicted very low values for biological oxygen demand, in agreement with field measurements. The model predicted reduced dissolved oxygen values in the middle (5-20 m depth) layer - slight in winter and significant in summer and high values at the top and bottom. This mid depth reduction was not in agreement with most of the earlier data. Further improvements in the accuracy of the results would require better parameterization of the biological parameters and switching to a time dependent scheme.

(c) Hydrodynamic: a two dimensional, vertically averaged finite difference numerical model was chosen to model the currents in the Harbour (ASA Consulting Ltd., 1986). The grid size was 400 m, the largest size that could reasonably represent the Northwest Arm and The Narrows (Fig. 4-1). The model was driven by an M2 tidal elevation at the outer boundary, tides being the dominant mixing mechanism over most of the inlet and mixing being very important to the dispersal of pollutants. Calibration was against the Halifax elevation record. In common with all such models, many processes cannot be covered explicitly, and so have to be parameterized. Here, the complete range of mixing processes, from subgrid scale to large scale and due both to tides and winds, was considered. Each individual process was formulated, evaluated and, if not explicitly included in the model equations, was assigned an equivalent eddy diffusivity (Table 4-1). Sensitivity analyses were done using a range of diffusivities. It was found that the eddies and tidal and residual circulation patterns in the outer harbour were very sensitive to choice of diffusivity values but that the strong tidal currents in The Narrows were not. Similar results were found with the range of possible values for bottom roughness. High values tended to reduce flow in shallow areas at times of high flow, and damp out eddies at times of low flows. This was particularly noticeable around McNabs Island.

(d) Water Quality Model: this uses the same grid as for the hydrodynamic model. The loading model supplies 16 distributed freshwater/sewage loads and 16 point sources around the shoreline. The hydrodynamic model supplies the currents at each grid box at each time step, and a value for the dispersion coefficient, 30 m^2/s. In a sensitivity test, the dispersion was reduced to 5 m^2/s. Significant reductions in spreading were seen only in the harbour mouth and in Bedford Basin-regions where wind induced mixing was relatively more important than tidal mixing. The reaction of the tracers being modelled is parameterized by a first order decay (fecal coliform) or a reaction (biological-oxygen-demand to dissolved-oxygen) relationship. Decay rates from 0.12 to 26.4 day^{-1} were found in the literature, the wide spread perhaps being because many examples from fresh water were included. Model runs covering the range 0.1 to 1.0 day^{-1} were performed and all the predictions were found to lie within the wide bounds (3-3000 coliform counts/100 ml) found for field data gathered in the summer in Halifax Harbour. Field data were uncorrelated with depth, time within a tide cycle, or tide range. The variations, although large and unexplained, are typical of coliform measurements generally. The modelling of dissolved oxygen is less accurate. It used only a simple first-order kinetic relationship to biological oxygen demand, ignoring any effect of phytoplankton/nutrient interactions. This was considered adequate for order-of-magnitude impact assessment. Simulations were run for a variety of time-averaged loadings, populations, and proposed treatment plant outfall locations. The outputs were contoured plots of tracer concentrations. A series of plots for coliform is shown (Fig. 4-2), (CBCL Ltd., 1987, Appendix D). From this one picture, one can draw several conclusions:

- The major improvement in water quality comes from the upgrade in treatment, from raw to primary, and not from outfall rearrangement.
- The area of direct contamination from an outfall is approximately constant. Its position and shape can be changed slightly by outfall placement.
- Even with a treatment plant putting in absolutely no contaminants, parts of the inlet would still be contaminated. This is because of runoff from streams, storm sewers and overflows from combined and sanitary sewers. On an annual basis, the coliform load from these untreated sources is comparable with that from the treatment plants.

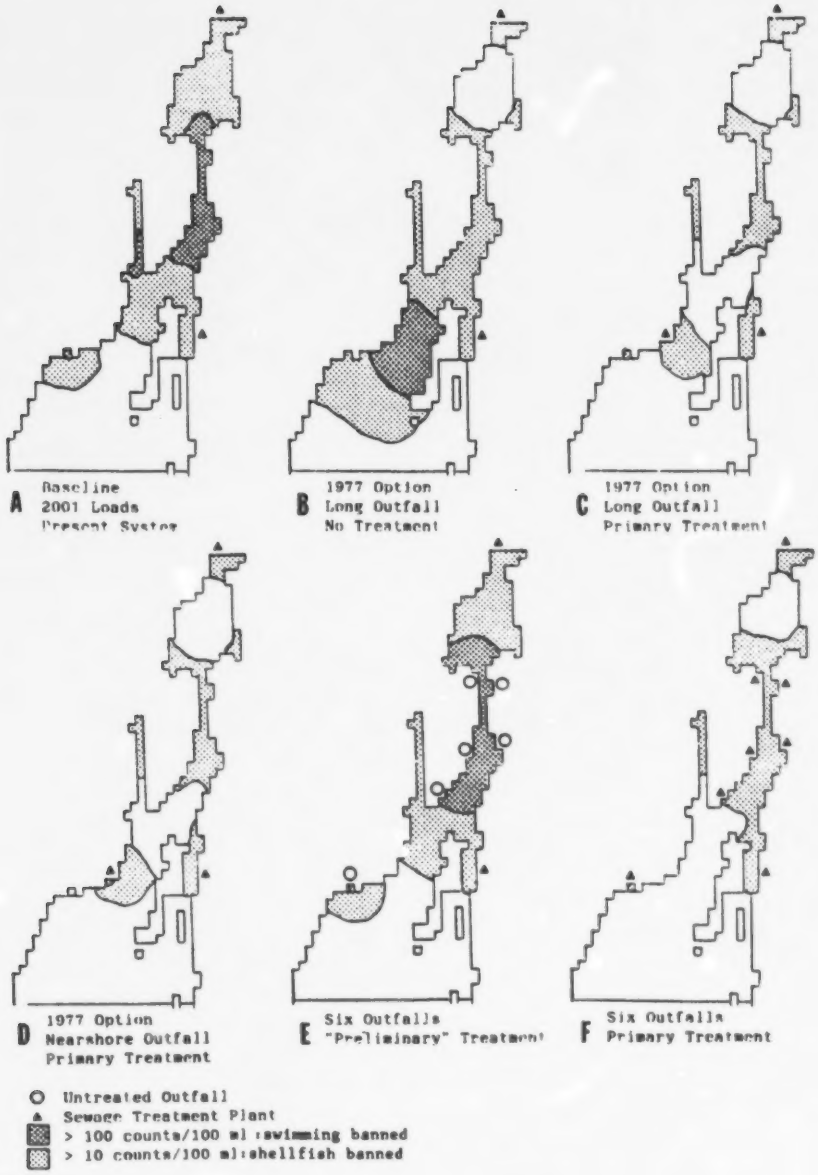

Figure 4-2. Predicted fecal coliform distributions for regional treatment plants versus distributed local plants. From ASA 1987 as Appendix D of CBCL 1987.

(e) Floating Debris Model: this uses the same grid as for the hydrodynamic model. A nominal loading of 1 particle per m^3 of raw sewage was used. The model superimposed a wind drift onto the hydrodynamic prediction of current, using standard values of reduction (3%) and rotation (10^o to the right). Using a 12 hour release time step, 20 years worth of simulations were done, to cover all combinations of measured wind and tide, and obtain statistically significant results even for areas of low incidence of debris. The results were presented as spatial distributions of surface concentrations and shoreline deposition rates. Sensitivity analyses showed low dependences on diffusion coefficient drift factor and decay rate, because drift distances and time were so short. No verification was possible due to lack of data on source strength or shoreline concentration.

(f) Diffuser Model: an analytical model was used at each of six possible outfall sites in order to get design parameters for a 50:1 initial dilution (CBCL Ltd., 1987, Appendix C). In all cases it was found that this could be achieved in about 20 m water depth.

FUTURE STUDIES

Taken from the presentation to the Halifax Harbour Cleanup Review Committee of the Nova Scotia Environmental Control Council (Lawrence, 1988), the following are offered as possibilities; the order is not significant:

- Fine tune several of the model parameters by measurements in strategic places. Several current meter moorings and tide gauges in several sites for a month or more might suffice.

- Include the Nova Scotia Coastal Current as a model driving force. The model boundaries might have to be extended, and several current meter moorings put on or near the boundary for several months or more.

- Consider an outfall site on the eastern headland. There is public pressure for this to be done. This might increase the need to model the coastal current.

- Model the deep intrusions into Bedford Basin to verify the understanding of the initiation mechanism, and then assess the impact. Extensive analysis of existing data has been done (ASA Consulting Ltd., 1986, Appendix B), but modelling was not possible due to lack of a model for water properties and motions on the Scotian Shelf. Several years of density and oxygen data might be needed.

- Carry out detailed measurements around one or more proposed outfall sites to determine non-tidal flows better. Single current meter moorings would do, for several months.

- Consider in more detail the effects of untreated runoffs, the statistics of occurrence and severity, with detailed plots in time of what goes on through a storm event.

Several of these points subsequently appeared as recommendations from the Halifax Harbour Cleanup Review Committee (Halifax Harbour Cleanup Review Committee, 1989), were broadened to include Lagrangian drifter studies and two-layer flow measurements, and then incorporated into the guidelines of the upcoming physical oceanographic study referred to in the introduction.

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APPENDIX A

HEAVY METAL, POLYCYCLIC AROMATIC HYDROCARBON, AND POLYCHLORINATED BIPHENYL CONCENTRATIONS IN AMERICAN LOBSTERS (*HOMARUS AMERICANUS*) FROM HALIFAX HARBOUR

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Although the lobster fishing season is open in the Halifax Harbour area from the last week of November to 31 May, there is virtually no fishing during the winter months from January to April. During this latter period lobster movement is limited because of cold water temperatures and more frequent north-east winds that increase water turbulence. Fishermen have found that the lobster capture rate is low during such conditions. However, in response to a demand for immediate information on levels of contaminants in lobsters, 57 traps were set and checked in the Halifax Harbour area over a 6 day period during the winter (18-24 January 1989) by a local fisherman. Trapped lobsters were believed to be part of the resident winter population and could provide an estimate of the levels of contaminants at this one moment of time. The relationship between the levels reported here and those in lobsters captured during the fishing season is unknown and has not, to our knowledge, been studied.

Lobster (*Homarus americanus*) were collected from three regions of Halifax inlet (1) Dartmouth Cove, (2) Bedford Basin (including Birch Cove (2a) and Basin mouth (2b)), and (3) Harbour mouth (including Georges Island (3a), Point Pleasant Park (3b), and Northwest Arm (3c) (Fig. A-1) for determination of cadmium (Cd), copper (Cu),lead (Pb), mercury (Hg), and zinc (Zn) in digestive gland and cooked meat. Polychlorinated biphenyls (PCBs), and a suite of polycyclic aromatic hydrocarbons (PAHs - see Table A-2) were measured in digestive gland only since this is the site of fat storage in this animal and these chemicals are known to accumulate in fatty tissues. The pooled meat from seven lobsters captured within one kilometer off the Herring Cove sewage outfall site at Tribune Head on 25 May, 1988 had previously been analysed for cadmium and very low levels (0.01 µg/g wet wt.) found.

Since the number of animals was small, three pooled samples of digestive gland and cooked meat were prepared from steam-cooked claws and tail from the animals. Pool 1 (Dartmouth Cove) consisted of 5 animals; Pool 2 (Bedford Basin) consisted of 4, 2 from Birch Cove and 2 from the mouth of Bedford Basin; and Pool 3 (Harbour mouth) consisted of 2 lobsters off Georges Island, 1 from the mouth of Northwest Arm and 1 from off Point Pleasant Park.

Analytical procedures for trace metals are described in Chou and Uthe (1978). Organics (PCBs and PAHs) were determined by gas chromatography and liquid chromatography respectively using electron capture and

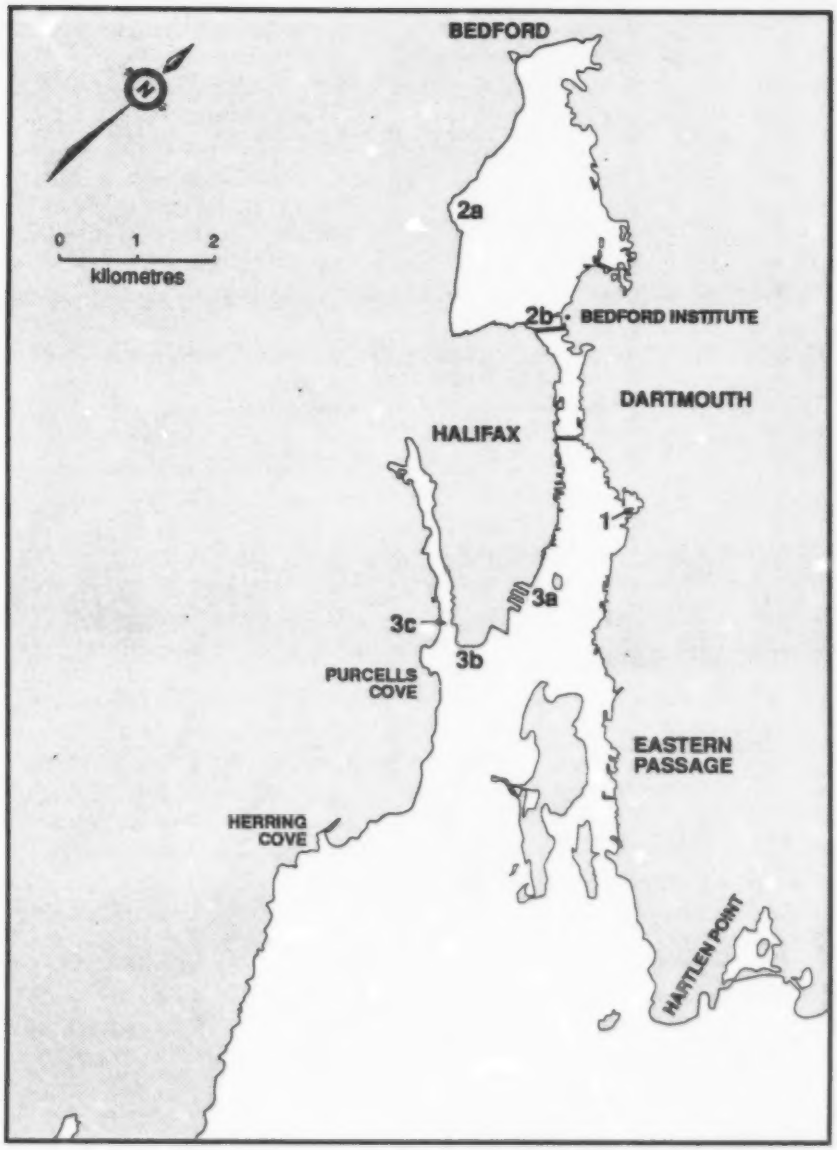

Figure A-1 Location of regions from which lobsters were collected.

fluorescence detection, as appropriate, following gel permeation cleanup of isooctane extracts of saponified tissue (Contract analyses - C.J.M.).

Because of the small number of animals captured, the pooling of animals captured over large sampling areas and the lack of commercial lobster fishing during this time of the year, it must be emphasized that these results cannot, in our opinion, be used for any other purpose than estimating the extent of contamination for human health considerations.

RESULTS AND DISCUSSION

Surprisingly low levels of cadmium were found in digestive gland, from 0.34 to 0.66 µg Cd/g which are substantially lower than the reported mean concentrations of 2-15 µg Cd/g reported in the digestive gland of lobster from non-contaminated areas (Freeman and Uthe, 1974). The Cd concentrations in cooked meat ranged 0.011-0.012 µg Cd/g wet wt. and are considered to be at or below background values (Uthe and Chou, 1985).

Cu concentrations in pooled digestive glands were 199 µg Cu/g for Dartmouth Cove, 69.7 µg Cu/g for Bedford Basin, and 35.6 µg Cu/g for Harbour mouth. Chou and Uthe (1978) reported that lobsters from Halifax area had a geometric mean digestive gland Cu concentration of 120 µg Cu/g (wet wt.).

They also reported geometric mean Cu concentrations in other areas, North Lake, PEI (12.9 µg Cu/g), Victoria Beach, NS (19.1 µg Cu/g), Shediac, NB (41.3 µg/g), and Petit Rocher, NB (24.4 µg/g). Earlier studies (Chou and Uthe, 1978) on lobsters held in Halifax Harbour water have shown a large range in Cu concentrations in the digestive gland with individual values >100 µg/g being relatively common. Copper concentrations in cooked meat were within the range reported by Uthe and Chou (1985) for lobsters from the Belledune area, including the controls. Note that this latter area is one that is contaminated with metals discharged from a local smelting and fertilizer industrial complex.

The levels of mercury in cooked meat and digestive gland were all well below the tolerance of 0.5 µg Hg/g wet wt. although a slight elevation may characterise the Dartmouth Cove samples. Freeman *et al.* (1974) reported mercury at levels of 0.25-0.73 µg Hg/g in tail and claw muscle of offshore lobsters.

Lead levels in lobster digestive gland and cooked meat from Halifax Harbour area ranged 0.076-0.262 µg/g. Lobsters from the Bedford Basin site had a somewhat higher digestive gland and cooked meat lead level than lobsters from Dartmouth Cove and Harbour mouth. Lead content in harbour cooked lobster meat from three sites studied are still much lower than the reported mean value of 1.14-1.20 µg Pb/g from Belledune Harbour (Uthe and Chou, 1985). However, the mean lead level in cooked meat from the control site, Heron Island, was 0.052 mg Pb/kg. All values are below 2.0 µg/g.

The concentrations of Zn in digestive gland ranged 20.8-25.0 µg Zn/g while cooked meat ranged 33.0-36.2 µg Zn/g and are within normal levels (Chou and Uthe, 1978). The reasons for the higher Zn as well as Hg levels in the cooked meat as compared with the digestive gland is not known.

In summary, Cd, Cu, Zn, Hg, and Pb concentrations in pooled digestive gland and cooked meat from Halifax Harbour area lobsters (Table A-1) are below levels judged to be hazardous to human health although there is some suggestion of elevations in certain areas of the harbour. Cadmium concentrations are surprisingly low, well below usual background levels, suggesting that harbour lobster are in a rather unique environment with regard to the biochemistry of cadmium.

Concentrations of PCBs in digestive gland pools (Table A-2) ranged 1.2-5.6 µg/g wet wt. Only the Dartmouth Cove sample, with 5.6 µg PCBs/g, is of concern since the tolerance for PCB in fish products is 2.0 µg/g. The chromatograms showed no hexachlorobenzene and, possibly, very low levels of p,p'-DDE which could not be quantified due to the presence of interfering chlorobiphenyl peaks.

PAH levels in digestive gland were higher than levels characteristic of clean areas (Uthe and Musial, 1986) but were lower than levels that led to the closing of the commercial lobster fishery in the South Arm of Sydney Harbour or the removal of creosoted timbers from lobster

Table A-1. Heavy metal (Cd, Cu, Hg, Pb, and Zn) concentrations (µg/g wet wt.) in digestive gland and cooked meat pools from Halifax Harbour lobsters captured in January, 1989 (triplicate analysis).

Sample Site	[Cd]	[Cu]	[Hg]	[Pb]	[Zn]
DIGESTIVE GLAND					
Dartmouth Cove	0.34 ± 0.02	199.0 ± 3.0	0.24 ± 0.02	0.164 ± 0.005	25.0 ± 0.6
Bedford Basin	0.66 ± 0.02	69.7 ± 1.6	0.11 ± 0.01	0.244 ± 0.017	24.5 ± 0.7
Harbour Mouth	0.65 ± 0.01	35.6 ± 3.4	0.13 ± 0.00	0.175 ± 0.021	20.8 ± 0.3
COOKED MEAT					
Dartmouth Cove	0.011 ± 0.001	26.8 ± 0.2	0.34 ± 0.02	0.076 ± 0.002	36.2 ± 0.5
Bedford Basin	0.011 ± 0.001	19.8 ± 0.3	0.19 ± 0.01	0.262 ± 0.045	36.1 ± 0.2
Harbour Mouth	0.012 ± 0.001	24.3 ± 0.5	0.31 ± 0.01	0.076 ± 0.001	33.0 ± 1.0

Table A-2. Polycyclic aromatic hydrocarbon (ng/g wet wt.) and polychlorinated biphenyl (µg/g wet wt.). Concentrations in digestive gland pools from lobsters captured in Halifax Harbour in January 1989.

PAH	Harbour Mouth	Bedford Basin	Dartmouth Cove
Phenanthrene	98	190	210 (200)
Fluoranthene	300	630	550 (610)
Pyrene	200	680	440 (450)
Triphenylene (UV)	70	190	190 (206)
Benz[*a*]anthracene	63	130	79 (100)
Chrysene	110	250	170 (180)
Benzo[*e*]pyrene	88	160	i.
Benzo[*b*]fluoranthene	63 11 (UV)	160 19 (UV)	150 (170) 17 (23) (UV)
Benzo[*k*]fluoranthene	46	85	82 (85)
Benzo[*a*]pyrene	74	140	130 (140)
Dibenz[*a,h*]anthracene	n.d.	n.d.	n.d.
Benzo[*ghi*]perylene	70	100	160 (140)
Indeno[1,2,3-*cd*]pyrene	50	57	96 (94)
SUM	**1190**	**2770**	**2270 (2400)**
Polychlorinated Biphenyls (expressed as Aroclor 1260)	1.2	1.4	5.6

(PAH by fluorescence detection unless noted (UV) for ultraviolet absorption detection. n.d. - not detected. i - interfering peak; could not be quantified.)

tidal pond impoundments. Levels are in the range of those in Sydney Harbour areas in which commercial fishing is still allowed. PAH levels appear somewhat elevated within the Harbour compared with Harbour mouth values. Little can be said regarding the extrapolation of these results to the commercial fishery. Earlier studies (Uthe *et al.*, 1984) have shown significantly different accumulation of PAH in lobsters held for a few months in summer or winter in a tidal pond constructed with creosoted timbers. These results do suggest the need for further studies on PCB and PAH contamination to document levels characterising the commercial lobster fisheries in the Halifax Harbour area.

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APPENDIX B

MICROBIOLOGICAL EXAMINATION OF LOBSTERS OBTAINED FROM HERRING COVE, HALIFAX AND SAMBRO HARBOURS

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In support of an investigation organized by the Department's Fisheries and Habitat Management Branch, the Microbiology Section of the Inspection Branch Scientific & Technical Services Laboratory, Halifax, N.S. conducted bacteriological analysis on 29 lobsters caught in various locations within Halifax and Sambro Harbours.

The laboratory examinations conducted are those routinely performed on domestically produced and imported fish or fishery products. Samples were harvested by commercial fishermen and transported to the Fish Inspection Laboratory by a Conservation & Protection officer as soon as possible after landing. All lobsters were alive and vigorous upon receipt at the laboratory.

The samples were collected on three separate dates. The first set were caught on May 24, 1988 near a municipal sewage outfall in Herring Cove. The second set were collected on June 14, 1988 from twelve locations within and around Halifax

Table B-1. Results of microbiological analyses of lobster samples taken from Herring Cove - May 24, 1988

Samples	Coliforms /100 g	F. coliforms /100 g	S.P.C. at 35°C	C. Perfringens/g	Salmonella
No. 1. Uncooked Lobster					
a) Surface	68	<20	120	20/100	Negative
b) Hepatopancreas	45	45	30	45/100	Negative
c) Intestinal Tract	1100	200	5500	<20	Negative
d) Tail Meat	<20	<20	<10	<20	Negative
No. 2. Lobster Cooked for 8 Minutes					
a) Hepatopancreas	Positive	Positive	300	Positive	Negative
b) Intestinal Tract	Negative	Negative	300	Positive	Negative
c) Tail Meat	Negative	Negative	<10	Negative	Negative
No. 3. Lobster Cooked for 15 Minutes					
a) Hepatopancreas	Negative	Negative	80	Positive	Negative
b) Intestinal Tract	Negative	Negative	400	Positive	Negative
c) Tail Meat	Negative	Negative	<10	Positive	Negative

and Sambro Harbours. The third set were collected on June 15, 1988 from seven locations within and around Halifax Harbour.

The first set of samples (Table B-1) consisted of three lobsters. Lobster no. 1 was examined uncooked while lobsters no. 2 and no. 3 were examined after being boiled in tap water for eight and fifteen minutes respectively. Each lobster was assessed for total numbers of aerobic bacteria by standard plate count (S.P.C.) at 35°C, coliform bacteria, fecal coliform bacteria, *Clostridium perfringens* and Salmonella. These analyses were conducted individually on the hepatopancreas, intestinal tract and the edible tail muscle on all lobsters. The surface flora of the uncooked lobster was estimated by washing the entire animal with an equal mass of sterile distilled water inside a sterile plastic bag and analyzing the resulting suspension. In anticipation of low numbers of micro-organisms after cooking, lobsters nos. 2 and 3 were assayed only for the presence or absence of specific groups of bacteria in order to increase the sensitivity of the test; therefore, no quantitative results could be recorded except for Standard Plate Counts which are reflected in Table B-1.

The second set of samples (Table B-2.) consisted of 12 lobsters from various locations within and around Halifax and Sambro Harbours. Based on information from the first set of samples, which indicated that *Clostridium perfringens* and total aerobic bacteria were not present in any significant numbers, only fecal coliform bacteria and Salmonella analysis was performed on the digestive tract of raw lobsters. Surface flora was not assessed due to the fact the lobsters had been in contact with each other during transportation.

The third set of samples (Table B-3.) consisted of 14 lobsters. Two animals were obtained from each of seven locations within Halifax Harbour. Fecal coliform bacteria and Salmonella analysis was performed on all the lobsters. One lobster from each site was assessed in the raw state for the bacterial content of its hepatopancreas and intestinal tract separately. The remaining lobster from each sample location was boiled in tap water

Table B-2. Results of microbiological analyses of the digestive tract of raw lobster samples taken from Halifax and Sambro Harbours on June 14, 1988

Sampling Point	MPN Fecal Coliforms/100 g	Salmonella
No. 1. Sambro	<30	Negative
No. 2. Sambro	<30	Negative
No. 3. Container Pier near Point Pleasant Park	72	Negative
No. 4. Lighthouse Bank	30	Negative
No. 5. McNabs Island, west side	<30	Negative
No. 6. Sandwich Point	<30	Negative
No. 7. Indian Point (St. Margarets Bay)	<30	Negative
No. 8. Bedford Basin near Bedford Institute	30	Negative
No. 9. Park between Dartmouth Shipyard and Dartmouth Ferry Wharf	110	Negative
No. 10. Ives Knoll	91	Negative
No. 11. South of MacDonald Bridge	230	Negative
No. 12. Georges Island Channel	36	Negative

for eight minutes and its entire digestive tract (hepatopancreas and intestinal tract combined) was assessed for bacterial content after cooking.

RESULTS AND OBSERVATIONS:

No Salmonella was found in any of the three lots of lobsters examined. The levels of *C. perfringens* were low in all tissue samples examined. The levels of the indicator organisms in the cooked lobster, that is, coliforms and faecal coliform bacteria were well within the Departmental guidelines for *E. coli*. It should be noted that coliform and faecal coliform assays, which detect groups of indicator organisms, would tend to over-estimate the specific member *E. coli*. The total aerobic bacteria count indicated the muscle tissue to be essentially sterile.

The results of this limited investigation did not reveal any specifics that would indicate that the bacteriological quality of these lobsters would pose a hazard to human health, providing that the lobsters are properly handled and cooked.

Table B-3. Results of microbiological analysis of lobsters samples taken in the Halifax Harbour on June 15, 1988

Sampling Station	Sample	F. Coliforms/ 100 g	Salmonella
No. 1 Park between Dartmouth Shipyard and Dartmouth Ferry Wharf	a) Hepatopancreas (raw)	30	Negative
	b) Intestinal Tract (raw)	2400	Negative
	c) Digestive Tract after 8 Minutes Boiling	<30	Negative
No. 2 Nova Scotia Hospital (adjacent to water tower)	a) Hepatopancreas (raw)	<30	Negative
	b) Intestinal Tract (raw)	<300	Negative
	c) Digestive Tract after 8 Minutes Boiling	<30	Negative
No. 3 Georges Island Channel	a) Hepatopancreas (raw)	430	Negative
	b) Intestinal Tract (raw)	300	Negative
	c) Digestive Tract after 8 Minutes Boiling	<30	Negative
No. 4 Queens Wharves	a) Hepatopancreas (raw)	<30	Negative
	b) Intestinal Tract (raw)	<300	Negative
	c) Digestive Tract after 8 Minutes Boiling	<30	Negative
No. 5 Bedford Basin near Bedford Institute	a) Hepatopancreas (raw)	150	Negative
	b) Intestinal Tract (raw)	9300	Negative
	c) Digestive Tract after 8 Minutes Boiling	30	Negative
No. 6 Sleepy Park	a) Hepatopancreas (raw)	72	Negative
	b) Intestinal Tract (raw)	<300	Negative
	c) Digestive Tract after 8 Minutes Boiling	<30	Negative
No. 7 Black Rock Beach	a) Hepatopancreas (raw)	150	Negative
	b) Intestinal Tract (raw)	1100	Negative
	c) Digestive Tract after 8 Minutes Boiling	<30	Negative

APPENDIX C

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